Methodologies for Investigating Gas in Water Bores and Links to Coal Seam Gas Development

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Executive summary

Introduction

Methane in water bores is a major concern in areas of coal seam gas (CSG) development. There are risks associated with ignition and asphyxiation in closed spaces around bores that create real concern. There are also other risks, such as gas lock in pumps, colour and odour impacts from water quality changes, toxicity due to other gases and build up of gases affecting the integrity of the bores.

To address these risks, there is a need for an appropriate monitoring, management and response strategy, commensurate with the risks. Responsibilities for these strategies are variably divided between the industry, government and private concerns. This report deals with the state of the art of methods for investigating gas in water bores and analysis of resulting data world-wide and historical presence of gas in water bores in the Surat and Bowen basins. Information from this report is to be used to investigate and respond to reports of increased gas content in individual water bores across a large area in Queensland. For such work to be effective, a good understanding of the processes for and limitations of measuring gas in water bores is critical.

Methods for undertaking investigations into gas in water bores

Methane is a colourless, odourless and non-toxic gas, but is an asphyxiant at a concentration of over 50 per cent in air. It is the largest component of the gas causing concern in water bores in the Surat and Bowen basins. Methane in water bores may be present as “free gas” and/or “dissolved gas”. Methane usually only exsolves from a still solution, if the concentration of methane in the fluid exceeds its dissolved gas saturation point or solubility. Gas solubility varies with temperature, salinity, and pressure: it decreases with increasing temperature and salinity and increases with increasing pressure. Coal seam gas-derived methane will often co-exist with other gases such as short chain hydrocarbon gases such as ethane, propane and butane, as well as carbon dioxide, nitrogen and hydrogen sulfide. The relative abundance of such hydrocarbon gases (and their isotopic signatures) may be used to determine the gas source.

For methane, the measurement is that of dissolved gas or as a free gas derived from a water sample in the bore. Ideally, the sample should be collected from deep within the bore close to the screen either by low flow pumping or an in situ device such as a diffusion sampler. However, the logistics of any sampling survey and the need for consistency means that techniques involving sampling at the bore head are used. Appropriate techniques reviewed include the inverted bottle method as used for both free and dissolved gas and gas extraction samplers. Unfortunately, measured concentrations are sensitive to the exact sampling protocol, the device used, the analysis technique, and even the water temperature, salinity, and pressure. A study in Alberta, Canada, suggested that discrepancies in presence of free gas in water bores was due to different sampling methods used by different firms conducting the sampling.

Methane concentrations have been shown to be highly variable in space and time. This variability can be related to real processes that cause methane concentrations to go up and down. Some studies have shown that sampling error and analytical error also contribute to this variability; this suggests that a certain number of duplicate samples should be part of any larger survey, perhaps one in ten, or repeated sampling at a single site to provide standard deviation information.

For a better understanding of the impact of coal seam gas extraction and depressurisation on methane in the groundwater resource as a whole, a more systematic sub-regional and regional strategy is required.

This will allow the identification of gradual or sudden changes, irrespective of cause, and understanding of periodic changes of methane that may not be of concern.

When analysing methane data, careful consideration should be give to the following issues:

- methane occurs naturally in groundwater and in the vapour phase of the unsaturated zone, especially in areas where there is coal seam gas;
- methane concentrations will have been exacerbated by depressurisation caused by pumping for water and conventional gas development over time, as well as exploration for oil and gas before any coal seam gas development occurred;
- changes in methane may be due to a range of causes other than coal seam gas development. In many cases overseas, investigation of complaints have found that poor maintenance of water bores resulted in microbially-mediated methane production as a cause of changes in water quality. Presence of nearby landfill sites may be another source of methane;
- the coal seam gas development is somewhat different from many other industries due to the number of extraction wells required at relatively close spacing, the areal extent of the development and the number of companies involved;
- variability with time of measured methane concentrations due to sampling and analytical error and processes leading to presence of methane in the water bore; and
- variability of concentration of methane and related constituents within each of the different sources of methane.

A strategy, designed to address this plethora of issues, will need a sampling and analysis methodology that is robust enough to provide consistent measurements with sufficient sensitivity to detect trends in time and spatial patterns. Overseas experience with various sampling protocols have shown that to consistently and reliably measure concentrations with sufficiently low variability, requires focus on training, adherence to strict protocols, including split and duplicate samples, and consistency in the information recorded. For example, in the San Juan Basin in the USA, such a rigorous approach has lead to the situation where it could be shown that apart from a few bores, the coal seam gas development has not had a measurable impact on the methane levels regionally. In Alberta, Canada, where different trained consultants were used, large inconsistencies between results were found, despite considerable guidance being given by regulators. Best overseas practice often has data stored on an audited transparent database, a practice that helped identify and resolve inconsistencies between different firms measuring methane.

The sources of methane, transport processes from those sources to the well, pathways through which this transport occurs and transformations that might occur along the way have been reviewed. This forms a basis for understanding how chemical and isotopic data might inform us about the causes of gas occurrences and possible mitigation measures.

Most methane in water bores is of biogenic or thermogenic origin. The general relationship is that gas sources grade from biogenic to thermogenic with depth. Biogenic methane production is the most common of the processes in shallow groundwater systems and involves bacterial decomposition of organic matter in the absence of oxygen through either fermentation of organic matter or reduction of carbon dioxide. These processes can occur under conditions found in both near ground surfaces, such as in wetlands, as well as at depths to several hundred metres below ground surface. Shallow sources include organic-rich soils, landfills and manure/sewage storage systems. Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material largely originating in ancient shales. Thermogenic gases typically originated at great (several 1000s of m) depths; however, over geologic time these gases may have migrated far from the original source area and subsequently accumulated at shallower depths. Thermogenic methane may be associated with a wide range of heavier hydrocarbon gases such as ethane and propane, as either gases or heavier long chain hydrocarbons found in crude oil liquids, and hydrogen sulfide. The ratio of methane to ethane and propane is a commonly used method to distinguish between microbial and thermogenic gases.

Coal seam gas extraction in water-saturated coals involves pumping groundwater from a well to decrease the water pressure until methane desorbs from the coal. The methane first dissolves in water. When the water pressure is decreased sufficiently for methane to exist largely as a free gas phase, the gas migrates to the point of lowest pressure which is the production well. However, the pumping for production is not the only way to create the pressure reduction needed for gas to form. Dissolved methane can exist in the groundwater near a water bore. When the water bore is pumped, water pressures in both the bore and the adjacent formation are decreased. Such a decrease in pressure can lead to methane degassing as water is drawn into the bore. Pressure declines due to pumping are exacerbated if the pumping rate is increased or if adjacent areas of abstraction start to overlap and interfere with each other or if pumping continues long-term. These declines in pressure could lead to enhanced methane degassing and migration from increasingly larger areas around the bore.

Methane migration can also be affected by water, oil and gas developments, i.e. when water bores or gas production wells provide conduits through the different geological layers. Such borehole breaches present a number of opportunities for leakage of fluids in the vertical direction. Experience in the USA has indicated that older wells producing oil and gas from deep conventional reservoirs are more likely to provide gas migration pathways to the surface than shallower and newer coal seam gas wells. For example, in the La Plata County part of the San Juan Basin, approximately 20% of the conventional wells required remedial cement or were plugged and abandoned, while during the same period, approximately 3% of the coalbed gas wells were found to require remedial cementation or were plugged and abandoned.

The ability to identify the causes of any high concentrations of methane in water bores or changes requires measurements of other constituents besides methane. For example, methane from coal seam gas or other deep geological sources can be distinguished using isotopes of hydrogen and carbon of methane and associated wet gas components. Because water from different sources may mix before arriving at the water bore, a measurement of other hydrochemical signatures of water may help distinguish these further. Other useful measurements are (i) the stable carbon isotope ratio of dissolved inorganic carbon, which may be used to identify any bacterial consumption of methane that has occurred between the source and the bore and (ii) the radioactive carbon isotope (^{14}C) which identifies a younger source of carbon originating from shallower groundwater unrelated to coal seams targeted for CSG extraction. The ability to conduct such forensic analysis obviously adds expense to any baseline or ongoing monitoring program and makes it difficult to tailor the program so that cost is commensurate with risk.

Occurrence of gas in water bores in Surat and Bowen basins

There has been a long history of methane, both in dissolved form and as a free gas, detected in existing water bores or during drilling for water in the Surat and Bowen basins, dating back to the beginning of the twentieth century around Roma. Since then, there have been several occurrences of gas being reported during drilling, in bores, or gas in bores igniting. Gases from micro-seeps at the land surface have been measured in the region in the 90's. Gas companies have been required by the Water Act to collect and analyse baseline samples and for the results to be sent to the Queensland Government. The collated results are presented here and show that methane is present in water bores across the region. The methane is found at higher concentrations above features such as faults and above known gas reservoirs. The concentrations of gas vary in time according to atmospheric and other others factors.

Ongoing studies in Surat and Bowen basins

There are a number of recent and current projects investigating issues related to methane in water bores. Perhaps, the most notable has been the study of gas bubbling in the Condamine River. Norwest has conducted a study which showed that the source of the gas was from deeper aquifers, but could not rule out any specific pathways or causes for any increase in gas bubbling. It is only through further monitoring and studies that these will become clearer. Some baseline studies of methane and associated chemistry are also conducted by research institutions on behalf of land-holders. Here we report on the measurement of atmospheric methane being done in three studies by different institutions. While such studies are generally aimed at accounting for greenhouse gases, the patterns with respect to time and space can help target management options at reducing methane emissions and also support our understanding of methane pathways to the land surface. Finally, the understanding of broader chemistry from the perspective of carbon storage and recovery, inter-aquifer leakage, organic contamination of groundwater and the study of methane production all provide useful baseline information for methane in water bores. In particular, a recent program by Geoscience Australia and the Queensland Government for the purposes of carbon capture and storage has many relevant measurements for baseline and forensic interpretation. There does appear to be good coordination between the hydrochemical studies although coordination on methane-specific aspects could be improved.

1 Introduction

The Coal Seam Gas Compliance Unit (CSGCU) in the Queensland Department of Natural Resources and Mines (DNRM) is responsible for investigating complaints associated with impacts to water bores from coal seam gas (CSG) development in the Surat and Bowen basins in Queensland. Increasingly the complaints are related to increased gas in bores causing problems with the operation of pumps in sub-artesian bores and causing blockages in distribution lines from artesian bores.

The CSGCU has contracted CSIRO to undergo a literature review to support decision making around the issue. Broadly, the review should address the issue of an accepted methodology for sampling, analysis, and data interpretation to address risks associated with gas in water bores. If a methodology could be accepted, it is believed that it would help to resolve uncertainties and disputes associated with gas in water bores in coal seam gas development areas. More specifically, the report includes:

- The occurrence of gas in water bores prior to the commencement of the coal seam gas industry in Queensland;
- Methods for undertaking investigations into gas in water bores including:
  - hydrochemical methods;
  - sampling techniques to collect representative groundwater samples of dissolved or free gas;
  - dissolved or free gas composition analyses including stable isotope composition; and
  - field measurement of in situ total dissolved gas pressure and volume;
- Methods for determining methane gas migration potential including gas migration processes and mitigating factors affecting vertical / lateral gas migration;
- Investigations undertaken into gas in water bores to date in Australia and in particular the Surat and Bowen basins including assessment of the occurrence, volume, stable isotopic composition and source formation of the gas.

An information sheet, “Methane Gas in Water Bores” (CSIRO, 2014) has been developed in conjunction with the review.

In addressing the topics above, the review recognises that:

1. Methane is the dominant gas of concern. Methane is associated with smaller concentrations of other gases and hydrocarbons. Some of these, such as H_2S (hydrogen sulfide), may create issues of odour (“rotten egg” smell) and toxicity. Others are useful for understanding the source of methane;
2. The risks of methane in water bores are broader internationally than problems with pumps and distribution lines;
3. Sampling is one component of a monitoring strategy aimed at addressing these concerns through the identification of risks, measurements of any relevant changes in state, identification of the causes of these changes, identification of likely mitigation strategies and determination of whether the mitigation strategies have been successful;
4. Understanding the variability in space and time of gas concentrations in water bores is necessary to underpin investigations of gas occurrence in groundwater aquifers; well constructed and tiered

baseline surveys provide key information to relate gas occurrence to appropriate sources and pathways; and that

5. Coal seam gas is not the only cause of increased methane in groundwater.

The review addresses each of the topics and sub-topics in the following order:

1. Methods for undertaking investigations into gas in water bores. Under this topic, the following sub-topics are discussed:
   a) A brief overview of the properties of methane, the major concerns of methane in water bores and mitigation measures to address these;
   b) Sampling of dissolved and free gas;
   c) Developing a monitoring strategy beginning with a baseline survey;
   d) Sources of methane, transport of methane from source to the water bore and transformations along the way;
   e) Impacts of water and gas development on increased methane; and
   f) Conducting a forensic analysis.
2. Occurrence of gas in Surat and Bowen basins: This topic provides a historical perspective of methane in water bores within the Surat and Bowen basins; along with other evidence of gas in water bores before coal seam gas development occurred.
3. Relevant studies in Surat and Bowen basins, and elsewhere in Australia: This topic provides an overview of projects currently being undertaken to address the issue in Queensland and Australia.

This review has been aided by many excellent analyses on the topic internationally. In particular, the paper by Jackson et al. (2013) was provided with the terms of reference. The authors of this paper were also senior authors on many of the analyses on the topic, information which supported this review.

2 Methods for undertaking investigations into gas in water bores

2.1 Properties of Methane and Associated Risks

Natural gas is typically accumulated in a subsurface reservoir - any rock formation with adequate porosity, fractures, or sorption potential that can store liquid or gas hydrocarbons. The different forms of natural gas are generally categorised into conventional and unconventional gas. Conventional gas is obtained from reservoirs that largely consist of porous sandstone formations capped by impermeable rock. The gas can move to the surface through the gas wells without the need to pump. Unconventional gas is generally produced from complex geological systems that prevent or significantly limit the migration of gas and require innovative technological solutions for extraction. The difference between conventional and unconventional gas is the geology of the reservoirs from which they are produced.

There are several types of unconventional gas such as coal seam gas, shale gas and tight gas. Coal seam gas is entirely adsorbed into the coal matrix. Movement of coal seam gas to the surface through gas wells normally requires extraction of formation water from the coal cleats and fractures. Shale gas is generally extracted from a clay-rich sedimentary rock which has naturally low permeability. Tight gas is trapped in ultra-compact reservoirs characterised by very low porosity and permeability.

Methane is the largest component of the gas causing concern in water bores in the Surat and Bowen basins. It is a colourless, odourless and non-toxic gas, but is an asphyxiant at a concentration of over 50 per cent in air. Many of the specific properties of methane can be found in Stalker (2013).

Methane in water bores may be present as “free gas” and/or “dissolved gas”. One of the analogies used to differentiate these two forms is that of the soda bottle. While the lid is sealed, pressure keeps the gas dissolved in the liquid. Removing the lid causes a drop in pressure, allowing the previously dissolved gas to form bubbles (exsolve[1]) and rise to the liquid surface as free gas.

Methane usually only exsolves from a still solution, if the concentration of methane in the fluid exceeds its dissolved gas saturation point or solubility (Jackson et al., 2013). For a sample at the land surface, the solubility at normal levels of atmospheric pressure is 24.7 mg/L (or 34.6 ml/L) at 20 ^{o}C and 20.7 mg/L (or 29 ml/L) at 30 ^{o}C (Wiesenburg and Guinasso, 1979; Hirsche and Mayer, 2009).

Gas solubility decreases with increasing temperature and salinity and increases with increasing pressure. The effects are non-linear in all cases. A temperature difference of 20 ^{o}C (between 10 and 30 ^{o}C) for fresh water (zero salinity) results in a difference in solubility of 10 mg/L. At 20 ^{o}C, methane solubility ranges from 25 mg/L for fresh water to 19.3 mg/L at 40,000 mg/L salinity (Figure 1).

Hirsche and Mayer (2009) cite the example of a 360 m column of water leading to a methane solubility of 863 mg/L at 25 ^{o}C. Pressure effects can lead to water degassing as it is brought from depth to atmospheric pressure at the surface. This is similar to removing the lid of a soda bottle resulting in free gas coming to the surface.

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[1] Gas to separate out from groundwater and form a free phase

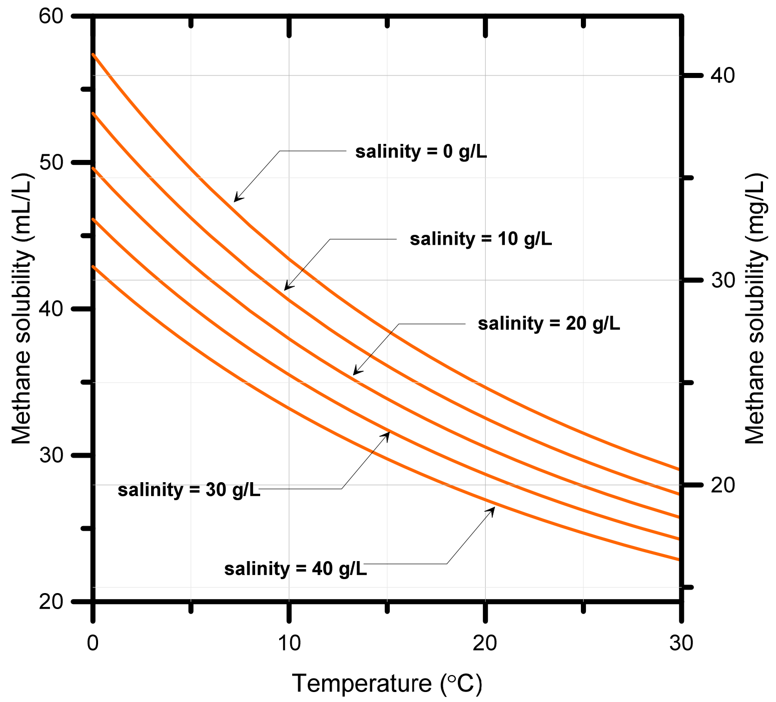

Figure 1 Methane solubility as function of temperature and salinity at atmospheric pressure (Based on data from Wiesenburg and Guinasso, 1979).

Agitation due to pumping and movement through samplers can lead to free gas release at under-saturated conditions. This is similar to shaking or heating a soda bottle, which causes more gas to bubble out.

Because it is odourless, methane can accumulate undetected in bores and bore enclosures that are not properly vented. Methane is extremely flammable and can be easily ignited by heat, sparks or flames. Methane is explosive at volumes of 5 per cent to 15 per cent (50,000 ppm to 150,000 ppm) in air. Methane is also an asphyxiant at a concentration of over 50 per cent in air. Although methane will rise, it can displace oxygen in confined spaces and hence such spaces can become vulnerable. Such risks can be mitigated through monitoring and proper ventilation. There are a number of useful sources of information on this (National Groundwater Association (NGWA), 2013a; NGWA, 2013b; Indiana Department of Natural Resources; Pennsylvania Department of Environmental Protection (DEP), 2011; Griffiths, 2007). Gas may also leak from the bore into the shallow sub-surface and then leak into closed buildings (Pennsylvania DEP, 2013). Some water quality issues can be treated with some form of treatment plants (Figure 2).

The bubbling of gas in water bores can also lead to other concerns. For example, it can affect pumps as the gas bubbles can lead to a "gas lock", in which the gas bubbles adhere to the impeller and impede the water flow. Harris et al. (2012) reported on the need to replace bore pumps due to the motors burning out as a result of "cavitation" when the dissolved gas comes out of solution. Pump shrouds or sleeves could be used or the type of pump changed (Figure 3; NGWA, 2013a). The shroud or sleeve is a tube open only at its base enclosing the submersible pump.

Gas bubbling can affect water quality in at least two ways. First, bubbles cause sediments that accumulate at the bottom of water bores to move through the water column, which in turn leads to water being used going from being clear to being "coloured, turbid, slimy, and smelly". Secondly, in certain circumstances, it can lead to the conversion of dissolved sulfate into "odiferous, noxious, and toxic" sulfides (Gorody 2012).

Under the most extreme circumstances, build-up of pressure may be great enough to dislodge the entire bore casing and pump assembly. At lower pressure, the water column can be gas lifted and promote artesian flow. It is not unusual to detect significant, yet short-lived, changes in water quality during such events, resulting from the mixing of deeper aquifer fluids with those of the shallow aquifer regimes.

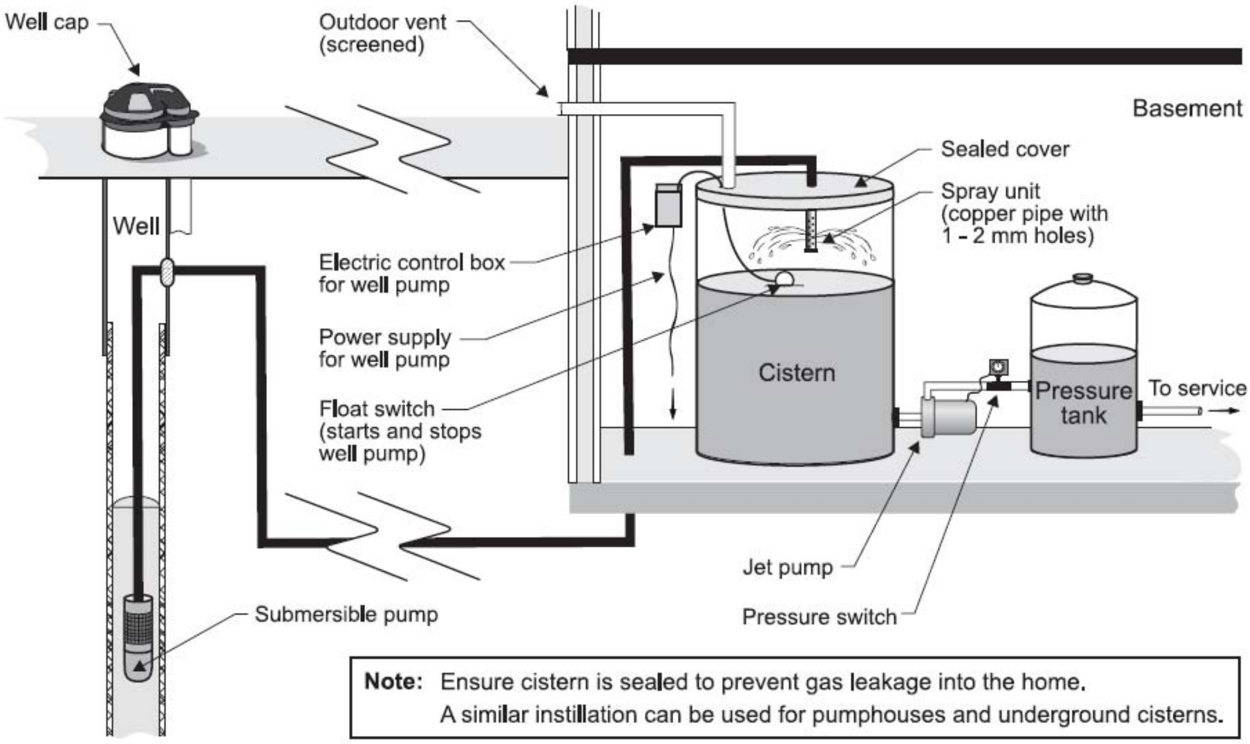

Figure 2 An aeration and ventilation system (Source: Agrifacts, 2006).

Alberta Environment's investigations indicate that, in the majority of complaints it investigates, the cause of water quality issues is not due to oil and gas activity (Armstrong et al., 2009). Inadequate water bore maintenance or the age of the bore is often determined to be the cause (Armstrong et al., 2009). Bacteria, such as iron and sulfate-reducing bacteria, can build up in bores that are not properly maintained, resulting in slime growth. In other cases, such bubbling may be natural or caused by pressure reductions from nearby bores. Dealing with water quality generally involves understanding and dealing with the causes of water bore nuisance aspects.

Coal seam gas-derived methane will often co-exist with other gases[2] such as short chain hydrocarbon gases including ethane (with its molecular formula C_2H_6, abbreviated as C_2), propane (C_3H_8, abbreviated as C_3) and butane (molecular formula for butane and its structural isomer 2-methylpropane is C_4H_{10}, abbreviated as C_4), as well as carbon dioxide and hydrogen sulfide. The last can lead to problems of odour, toxicity, and corrosion of casings and pipes (Moore, 2012).

Fortunately, methane gas is readily detected. Methane is sometimes recognizable as an effervescing[3] gas in the bores. In some cases, the release of methane in a water bore may be recognized by a sound similar to that of boiling water. Harris et al. (2012) report on anecdotal evidence from landowners referencing 'gassy' bores,' burping' bores, flaring bores and rumours of lighting farmhouses from the gas produced from the

[2] CSG contains 94-98% methane (Sydney Catchment Authority, 2012). The Santos CSG is typically 94% methane, 4% nitrogen, and 1% carbon dioxide (Santos, 2009a)
[3] The escape of gas from an aqueous solution and the foaming or fizzing that results from a release of the gas

water bore. Griffiths (2007) reports that ’ The usual evidence of gas is spurting water at a tap that is turned on quickly after it has not been used for a while and a milky colour to the water during the first few seconds.’ Any of these should cause the bore owner to obtain a measurement of free gas and/or dissolved gas. Such measurements are described in the next section.

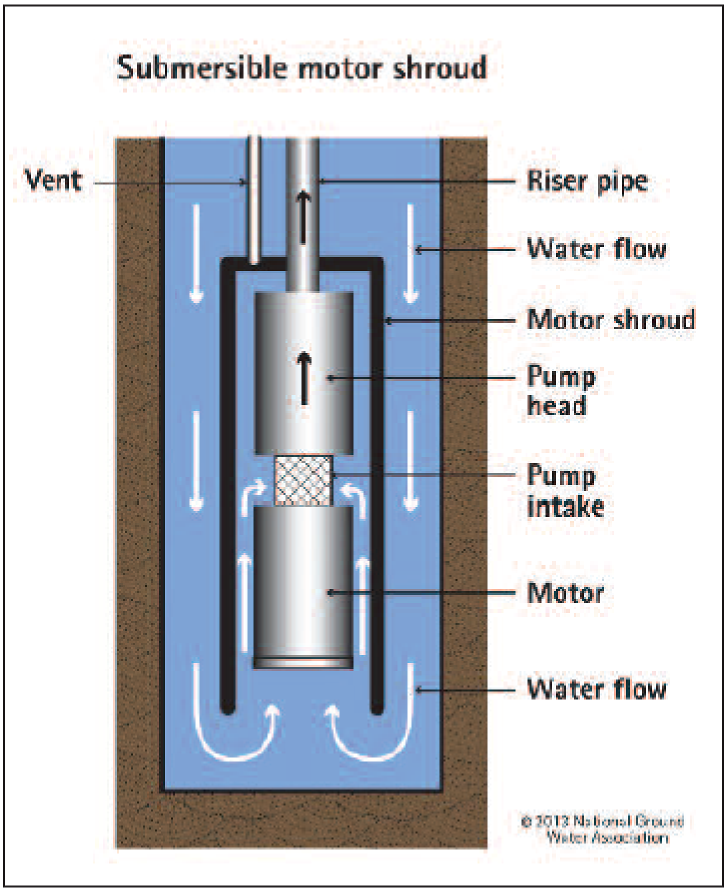

Figure 3 Schematic showing a pump shroud to avoid gas lock (Source: NGWA, 2013b).

As shown later, methane has been found in water bores in the Surat and Bowen basins over the last 100 years. In many cases, it has been something that locals have learnt to deal with. However, there has been an increasing number of potential ways in which methane can occur in shallow groundwater and water bores. Any sudden or widespread increases in methane in bore water may reflect problems that need to be addressed.

2.2 Sampling of Methane in Water Bores

In 2006, the Alberta Energy Resources Conservation Board issued Directive 035. This directive mandates that coal seam gas operators offer to test all active water bores within a 600 m radius of a proposed coal seam gas bore under given conditions. A Science Review Panel (Science Review Panel, 2008) found that there was a clear discrepancy between different environmental consulting firms conducting the sampling and analysis in the fraction of bores sampled that produce free gas. For instance, as of December 2007, the firm that conducted the largest number of tests (979) found free gas in 24% of the bores sampled. Other firms report even higher fractions. In contrast, the firm that conducted the second largest number (892) found free gas in only 2% of bores sampled. The Panel noted that many of the samples were collected in overlapping geographic areas and therefore such a large difference in the fraction of bores producing free gas is unlikely to be due to chance. This suggested that the sampling methods may have a significant effect on whether or not free gas is observed and subsequently analysed.

The objective of the sampling strategy has a large impact on the type of sampling and analysis being undertaken. In the above case, the sampling focussed on identifying whether gas exsolution may occur during pumping (is there any dissolved gas present), rather than determining the dissolved gas concentration. This would help determine if there were any likely risks associated with the build-up of gas. Hence, the methods encouraged more rapid pumping and sampling methods that would more likely cause gas to exsolve. Also, the coal seams producing the gas were above the water table. Thus, the result has been heavily influenced by the sampling and analysis method (Armstrong et al., 2009).

This section will describe sampling methods, while the next section deals with the monitoring strategy. Generally, the following steps need to be considered as part of sampling and analysis: 1) purging of the bore, 2) taking the sample itself, 3) transportation and storage, and 4) analysis. For this report, we will be considering the first three steps. Geoscience Australia (Sundaram et al., 2009) has developed some detailed protocols for groundwater sampling in Australian conditions. There are a number of international documents dealing with sampling methods, including those used in Alberta (Hirsche and Mayer, 2009), and the USA (Koterba et al., 1995; Stolp et al., 2006). Taken together, these provide descriptions of a wide range of techniques and the pros and cons of each. We will not describe detailed protocols here but refer the reader to these documents. It is also worth noting that methane is not usually the only constituent sampled, but others will be as part of any monitoring or required for forensic analysis, as described later in the report.

2.2.1 SAMPLING OF DISSOLVED GAS

Purging/sampling

The methods for purging and subsequent sampling are important to provide consistent analyses. Criteria for choosing any given method include i) it must be comparatively simple while ensuring reliable and accurate results, and ii) accessibility to the bore itself. Sampling can occur at above-ground access points, or by using down-hole sampling devices. Techniques where pumps and other sampling equipment can be placed down the bore are preferred over above-ground sampling; the latter techniques are known to suffer from pumping-induced pressure changes that may affect the dissolved gas concentration due to degassing during pumping (Hirsche and Mayer, 2009).

Caution must be exercised when pumping bores prior to sampling. Especially pumping of gassy bores leads to de-gassing and therefore might not be safe. In such situations, snap (ProHydro, 2014) or diffusion sampling techniques are recommended.

For some existing production water bores, it may be necessary to use existing pumps and this restricts the range of methods. Purging is necessary (depending on the use of the bore) as any stagnant water in the bore is likely to have degassed, and chemical reactions in the bore are likely to modify some of the other chemical parameters. Usually, purging involves removal of 3 casing volumes of standing water, if possible (ASTM, 2012). Field parameters such as pH, temperature and EC are monitored during the process and help provide a guide to whether a sufficient volume has been pumped; stabilisation of such parameters is used to indicate sampling can begin. Purging based on stabilisation of these parameters is more suitable for bores with low yields or in cases where the landowner will not allow purging of three bore volumes.

The process of pumping, well recovery and bringing the sample to the surface is likely to lead to degassing. Figure 4 shows the response of the total dissolved gas pressure to pumping. The measurement of total dissolved gas pressure is an in situ measurement. Where possible, it has been recommended as part of the monitoring and analysis program (Roy and Ryan, 2011).

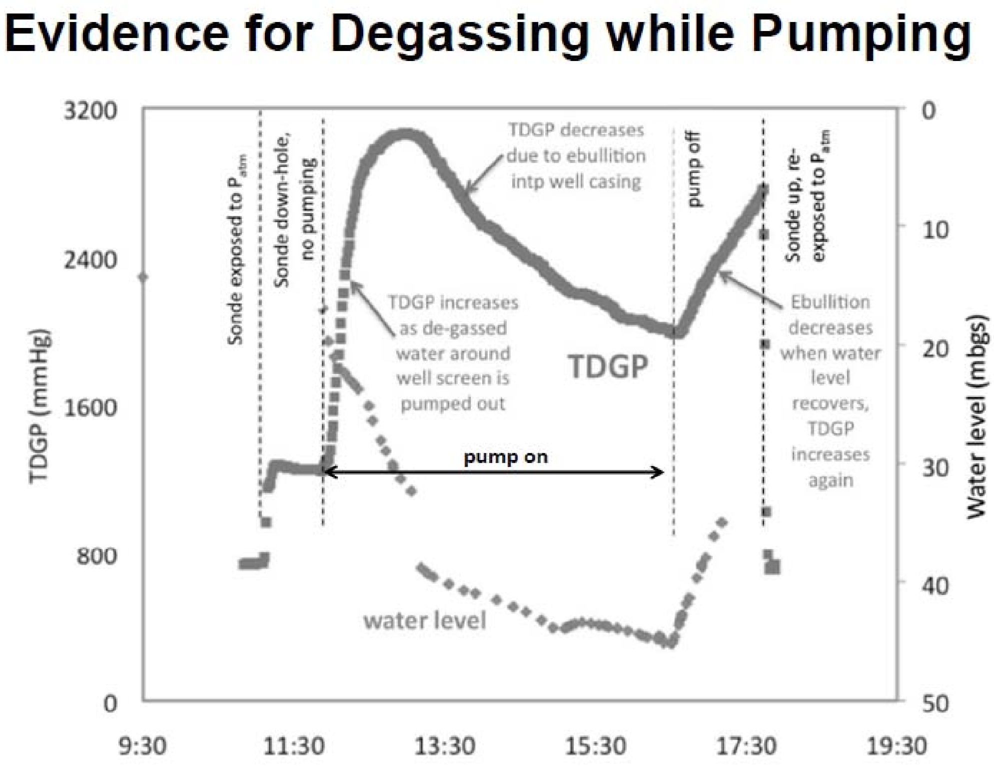

Figure 4 Response of the total dissolved gas pressure (TDGP) to pumping (Source: Roy and Ryan, 2011).

This degassing issue gives impetus to the application of down-hole methods. The US EPA (2010) encourages the use of low-flow sampling. The low flow pumps are placed close to the screens and are meant to pump at a rate comparable to the inflow to the bore. In this way, there is as little disturbance possible for the water in the bore.

Down-hole diffusion cells may also be used. Barber and Briegel (1987) developed a sampler that required relatively little time for gas in the sampler to equilibrate with that in the groundwater. There have been some recent developments to simplify the design and to improve the precision of measurements. There are also a range of non-diffusion samplers. These come in various degrees of complexity and work under a range of physical principles (Hirsche and Mayer, 2009). However, for broader surveying, such techniques can be labour- and time-intensive.

Taking the sample

Assuming the water is discharged from the bore in some form or another (i.e. not using the passive in situ approaches), one needs to capture the water sample itself. The most common approach is that of the inverted bottle method as this can be used where there is access at the surface. Geosciences Australia (Sundaram et al., 2009) provides a detailed description of a protocol, which is an adaptation of the USGS approach (Stolp et al., 2006). This allows quantitative concentrations of the dissolved gas per volume of water to be obtained. The method relies on discharging bore water into the bottom of a serum bottle until full. The bottle is then submerged into a bucket of water and the operator continues to discharge water until the bottle has been purged by two volumes. This needs to be done, without having bubbles adhering to the side of the bottle. A stopper is placed in the bottle and then crimp sealed with aluminium crimp caps.

The primary disadvantage of the method is the difficulty of avoiding bubbles and providing a good seal. Accurate measurement requires exemplary sampling. A poor seal will results in equilibration of the dissolved gases with the atmosphere during storage and transportation and a lower estimate of the true dissolved gas content. To obtain reproducible results, it is important to keep sampling procedures as consistent as possible.

An alternative to this method is the bubble strip method (Kampbell and Vandegrift, 1998). The method is based on the principle that gases will undergo a partitioning between a vapour phase and a liquid phase that are in contact with each other. The stripping procedure involves filling the gas sample bulb with the water solution being analysed and then introducing an inert gas (e.g. 20 mL) to the sampler. The water sample continues to be pumped through the sample bulb, which causes agitation in the aqueous phase. The agitation of the pumping helps the partitioning of the dissolved gases between the two phases until equilibrium is reached. When equilibrium is reached, a syringe is used to sample gas. The main difficulty is that the agitation may cause excessive degassing. It is also more difficult to use than the static headspace equilibrium method, described in a little while below.

Transportation and storage

Samples must also be kept at 4°C at all times to lower the rate of microbial degradation and minimise sample loss. Samples cannot be frozen and should be shipped for analysis within several days of collection.

Separating dissolved gases from water samples

As soon as groundwater samples containing dissolved gases are collected, the dissolved gas has to be separated from the water sample prior to chemical and isotopic analyses. Two commonly applied methods are the static head space equilibration technique and the vacuum ultrasonic method.

The static headspace method is used with samples taken either by the inverted bottle method or downhole methods. Preparation of the sample at the analytical laboratory or in the field requires creating a headspace in the sample bottle (typically with helium or other inert gas). A syringe is used to equilibrate with the atmosphere. The sample is then shaken for enough time for equilibration of gases. An aliquot of the headspace is withdrawn and analysed using gas chromatography. It is important that there is no contamination with atmospheric gases and sufficient time is allowed to equilibrate. There are a number of variations of the method in which sample bottles are not always full, different gases are used and different equilibration times.

An alternative method is the vacuum ultrasonic method in which water samples are subject to ultrasonic agitation while in a water bath. The released gases are carried under vacuum to another place of the apparatus and then sampled using a syringe. A reported difficulty is that ultrasonic agitation may break down short hydrocarbon chains (Hirsche and Mayer, 2009).

Analytical techniques

The chemical analysis of dissolved gases and free gases obtained from water bore samples is conducted by gas chromatography (GC) using various detectors. A discussion of the different types of gas chromatographs, detectors, carrier gas, columns, temperatures etc. is beyond the scope of this review. Further details are available from Hirsche and Mayer (2009).

2.2.2 FREE GAS SAMPLING AND ANALYSIS

Analysis of entrained/evolving gases is not a widely used monitoring practice in Australia, but has been used with some success for hydrocarbon prospectivity in Australia (Sundaram et al., 2009). The technique is particularly suitable for semi-quantitative field analysis of gases, particularly methane and carbon dioxide. While the degree of quantification is less than for dissolved gas analysis, the samples do not require refrigeration, and, if field analysis is conducted, there is less chance of contamination (i.e., gas loss) during transportation and storage. This technique can be used for sampling groundwaters at elevated temperatures, where collection of dissolved gas samples is either too hazardous or where a high proportion of the dissolved gases may have volatilised (Sundaram et al., 2009).

Sampling methods

The sampling techniques rely on depressurisation of water samples. The most simple of these is the inverted bottle method for free gas (Figure 5). As water is brought to atmospheric pressure, gas is released. A bottle with no gas is purged with at least two volumes of water. Once sufficient gas is exsolved, the bottle is capped. Pumping rate is used to estimate the volume of water producing the gas. The bottle is transported upside down to point of analysis. A variation of this method is to provide a throttle to encourage gas to exsolve from solution.

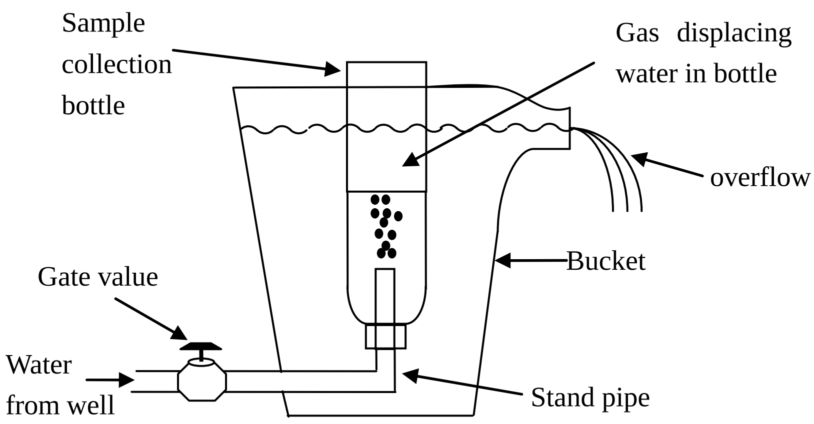

Figure 5 Inverted bottle method for free gas sampling (Modified from Keech and Gaber, 1982).

A reasonably common throttle is the use of flow through samplers (Figure 6). Most samplers consist of a plastic or glass sampler with a metal cone-shaped tube and three valves: 1) an inlet valve for water 2) an outlet valve for water and 3) extraction point for gas. The sampler is first filled with water, and then the water exit valve opens with some water exiting through the gas sampling point. The inlet valve is subsequently closed until no water leaves through the gas extraction point. When the gas valve is closed, water should be at even pressure. As water passes through the end of a metal tube, gas is released and floats to the top of the sampler. When there is sufficient gas, a gas sample is taken. Again, the volume of water is estimated.

While such samplers are practical to use, each type of sampler has a different shape and different protocols. This leads to inconsistencies in analyses between instruments. While some of the instruments have specified efficiency of degassing under given conditions, this is not always the case. In some cases, the samplers cannot handle the discharge from the bore and a T-junction may be required.

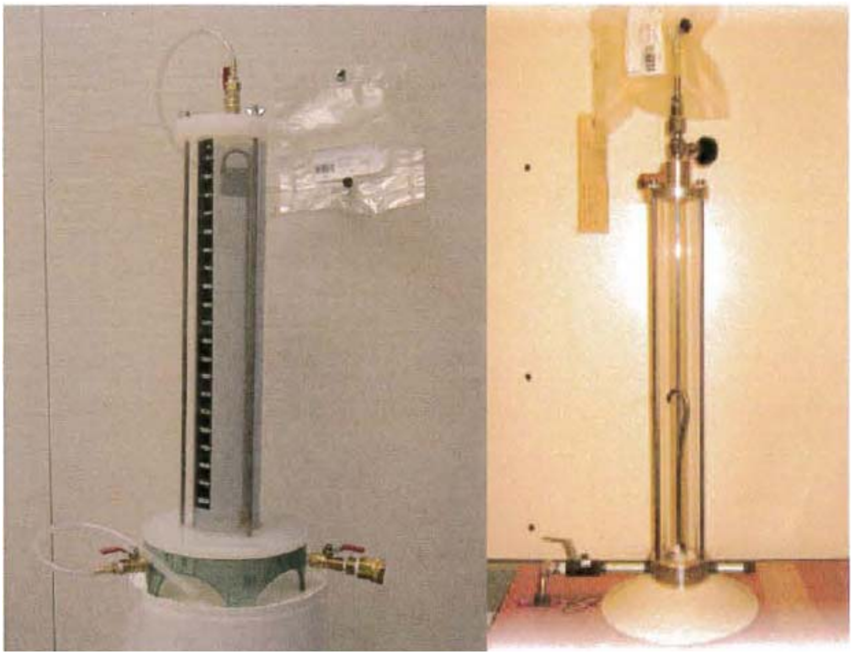

Figure 6 Flow-through sample cells (Source: Hirsche and Mayer, 2009)

Transportation and storage

The main criteria for adequate transporting and storing samples is to ensure leak-tight containers and prevent chemical or biological conversion of the gas components of interest. Commercially available electro-polished stainless steel containers are highly suited for this purpose. Typically, analyses should be done within a month from sampling and within a week if H_2S is present. A cheaper alternative is the Tedlar or Flexifoil Bags, which can store samples for a few days. Glass vials with grey butyl stoppers can be used for longer times.

Van Holst et al. (2010) tested various containers for long term storage of both CO_2 and methane. They recommended that only stainless steel cylinders, aluminium cylinders and aluminised five-layer bags be used for long term storage of gases.

2.2.3 REPEAT SAMPLING AND ANALYSIS

Methane concentrations are notoriously variable in time. Yet, very rarely is more than one sample collected.

Sampling and analytical error are part of the cause of this variability. A case study in which duplicate samples collected successively using careful methods, were shown to have about a 6% difference between minimum and maximum samples (Gorody, 2012). On the other hand, a study using split samples sent to different laboratories showed about a 40% variation, presumably due to calibration errors (Gorody, 2012). This suggests that a certain number of duplicate samples should be part of any larger survey, perhaps one in ten.

The same case studies showed that samples collected within a 95 day period and analysed by the same laboratory had about a 14% variability and a longer-term variability of about 25%.

As will be discussed in the next section, there are a range of physical reasons for this variability. For situations where we want to see how concentrations may change over time due to causes such as coal seam gas development or repressurisation of aquifers due to capping, we need to look at changes greater than the variability and hence we need to understand the variability. Also, if we want to look at causes for methane occurrence, we also need to understand the variability not only in the bores but also of the potential sources of methane.

2.2.4 SUMMARY AND DISCUSSION

This chapter highlighted the properties of methane and how this was linked to potential risks and also how we might monitor methane concentrations. The effort that goes into any monitoring program needs to be commensurate with the risks and tailored to highlight mitigation measures. For some of the risks, there is a well-established mitigation process established and some of this may not require an expensive monitoring program. However, for evaluation of the larger effects of the impacts of a coal seam gas development or for better delineating causes of poorer bore quality, one does require monitoring that is more comprehensive and consistent. Regular duplicates need to be part of that scheme. Where there is only above-ground access to bores, there will be issues of variability due to the effects of pumping samples to the surface and then analysing them. For a larger baseline program, this might be the only practical approach.

2.3 Monitoring strategies

Monitoring is done throughout the development of a new coal seam gas field, starting from before any development occurs (baseline monitoring) and finishing well after decommissioning. The purpose of the monitoring is to:

- identify any potential risks;
- measure changes in state of individual water bores and groundwater resource that might possibly have been caused by methane;
- identify causes for any changes; and
- target mitigation measures.

Monitoring can be related to an individual bore, but also to a sub-regional or regional groundwater resource. For the individual bore within a region, where methane is found in the ambient groundwater, the landholder often has lived with evidence of methane for some time. Typically, this includes evidence in drilling logs, signs of gas in water, gurgling sounds and problems with pumps (see section 3). Monitoring provides objective input to the owner on which to make decisions on measures that he or she may undertake with respect to ventilation, bore-works, pumps, bore maintenance etc. Such monitoring, if repeated regularly, may provide data about any sudden changes in methane concentration. The sampling of gas within the bore head using a commercial gas analyser can provide immediate and direct data on the specific risks of ignition. The accuracy of actual concentrations, however, are subject to a range of processes. To make this a reliable estimate, especially for its applicability to understanding trends and its reliability about emerging risks, measurement of methane concentration of both dissolved gas and of free gas, which has come out of solution, is required.

For a better understanding of the impact of coal seam gas extraction and depressurisation on methane in groundwater resources as a whole, a more systematic sub-regional and regional strategy is required. This supports the identification of sudden changes, irrespective of cause, that may potentially affect multiple landholders. It further promotes an understanding of the periodic changes of methane that may not be of concern.

To measure changes in state of individual water bores and the groundwater resource as a whole requires, in the first instance, a baseline survey across relevant bores and then sampling at time intervals afterward. For any detection of change or trend, the change needs to be larger than the noise in the baseline. This noise could be due to variability related to sampling and analysis but it also can be related to real processes that cause methane concentrations increase and decrease. Some of these processes will be described in the next section. To provide confidence about the extent of change, it is important to get some sense of the variability of the analyses. Conversely, the lower the analytical variability is, the more likelihood there is of detecting any trends.

For any area where coal seam gas occurs, there is always likely to be some natural levels of methane in groundwater and in the vapour phase of the unsaturated zone. These levels would have changed as a result of bores, respectively wells being installed for extraction of water and oil and also due to depressurisation caused by pumping for water. However, because of the lack of suitable monitoring, there is little evidence as to whether there has been an increasing level of methane. In addition, there are other biological sources of methane caused by man’s activities. For example, lack of bore maintenance or presence of nearby landfills can be sources of methane production. For these reasons, it is more difficult to obtain a baseline level of methane than if all methane was due to coal seam gas development.

Some of the overseas experience points to the need for rigorous protocols and training around determining natural levels of methane if the variability is to be both known and sufficiently small to detect changes. In the San Juan Basin in the USA, such a rigorous approach has led to the situation where it could be shown that apart from a few bores, coal seam gas development has not had a measurable impact on methane levels regionally (Gorody et al., 2005). Because of the natural variability of measurements, it is not feasible to make such an assessment in Alberta, Canada (Alberta Environment, 2006). However, some individual bores had such increases in methane in their water over time that clearly suggested there was a problem. These were investigated and most changes were found to be due to reasons other than coal seam gas. In the Marcellus Basin, the monitoring was able to show regional trends, as well as identifying some individual bores that needed addressing. But, after some debate about the interpretation, the weight of evidence is suggesting that the gas industry is affecting the groundwater (Jackson et al., 2013).

Many of these overseas case studies adopt a common database. The Alberta Science Review Panel (Ryan, 2008) made several recommendations to improve the database, so that it could form a basis for making decisions. It was only through this exercise that the magnitude of the inconsistency between different consultants measuring methane became apparent. It was also the debate in Colorado about the initial measurements of methane that led to more emphasis on understanding the variability and improvement of the sampling protocols. Similarly, the initial debate in the Marcellus Basin had led to much more focussed measurements.

As will be shown, methane will not be the only constituent measured as part of any survey. Apart from there being other risks, there is a need for other constituents to be measured to interpret the causes of any change. Many of these analyses are expensive. This raises the issue of the cost of monitoring being commensurate with the risks involved. If there is a need for rigorous measurements, taken over long enough time to detect trends, and for a range of analytes, there is a need for a process that maximises information while minimising cost (NSW Chief Scientist & Engineer, 2014a). It may not make sense to spend much more on monitoring than it would take to implement measures such as venting, pumps and water treatments everywhere.

However, it has been found that leaks through disused bores or through production bores can cause some serious risks for several landholders locally and may also have impact on a regional water source for a lengthy time. A more problematic situation exists if a local industry is dependent on that source of water, or requires infrastructure that becomes at risk. A further risk is that to people that may be within confined spaces within buildings. There are also reputational risks to industries, which could be affected by public perceptions of either industries being no longer viable or seeming to cause unreasonable damage to the environment.

Risks may need to be considered by government, industry and individual landholders. For each of these, the risks are different and the roles in managing risk are different. Hence, the type of monitoring each may be engaged in is different. Under the 2010 amendments to the Queensland's Water Act 2000, each coal seam gas proponent is required to undertake baseline surveys in their tenements. This does not prevent land-holders from undertaking their own surveys. The Cotton Research and Development Fund is supporting a project led by Associate Professor Bryce Kelly from the University of New South Wales in conducting a baseline survey and other analyses to support a forensic evaluation. The University of Southern Cross is providing a service for landholders in the northern NSW region (part of the Clarence-Moreton Basin) to have their water samples tested. The Queensland Government is the custodian for a database containing data submitted by Industry proponents. They also maintain a data base of drilling logs that should report gas shows in a well.

Once the issues are identified, there is a need to move to retrospective or forensic studies. These aim to identify causes for any changes, target mitigation measures and ensure these measures are working. In some cases, the identification may need to be unambiguous, the data defensible and there may be the need to prove that any defined threat is removed. Before going into these studies, the next section discusses the sources, transport and consumption of methane.

2.4 Processes

This section discusses the sources of methane, transport processes from those sources to the bore, pathways through which this transport occurs and transformations that might occur along the way. This forms a basis for understanding how chemical and isotopic data might inform us about the causes of gas occurrences and possible mitigation measures.

2.4.1 METHANE SOURCES

Most methane in water bores can be attributed to two types of processes: Biogenic or thermogenic methane production (Moore, 2012). Abiogenic methane is produced under strongly reducing conditions found deep within the earth's crust and is not significant to the current discussion.

Biogenic methane production is the most common of the processes in shallow groundwater systems. Biogenic methane is produced by bacterial decomposition of organic matter in the absence of oxygen through either fermentation or reduction. These processes can occur under conditions found in both the near ground surface, as well as at depths to several hundred metres below ground surface. Shallow sources include organic-rich soils, landfills and manure/sewage storage systems. Gas derived from such shallow sources have likely only had a short time to develop, and may have limited resources (e.g. carbon pools). Thus, although the accumulation rate might have been rapid, the accumulated volume in potential reservoirs might be relatively small and localised, especially in the absence of an upper low permeability cap. Furthermore, the slow transport mechanisms and the short time for migration after such recent gas production mean that the location of these gas deposits is usually coincident with the source, in the absence of pumping.

Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material largely originating in ancient shales. This process generally occurred after organic matter was buried under a sufficient thickness of sediments to generate the high temperatures and pressures required for gas generation. Thermogenic gases typically originated at great depths (several 1000s of m); however, over geologic time these gases may have migrated far from the original source area and subsequently accumulated at shallower depths. Thermogenic methane may be associated with a wide range of heavier hydrocarbons such as ethane (C_2) and propane (C_3), as either gases or crude oil liquids, CO_2 and hydrogen sulfide (H_2S). The ratio of methane to ethane and propane ($C_1/(C_2 + C_3)$) is commonly used to distinguish between microbial and thermogenic gases (Figure 7).

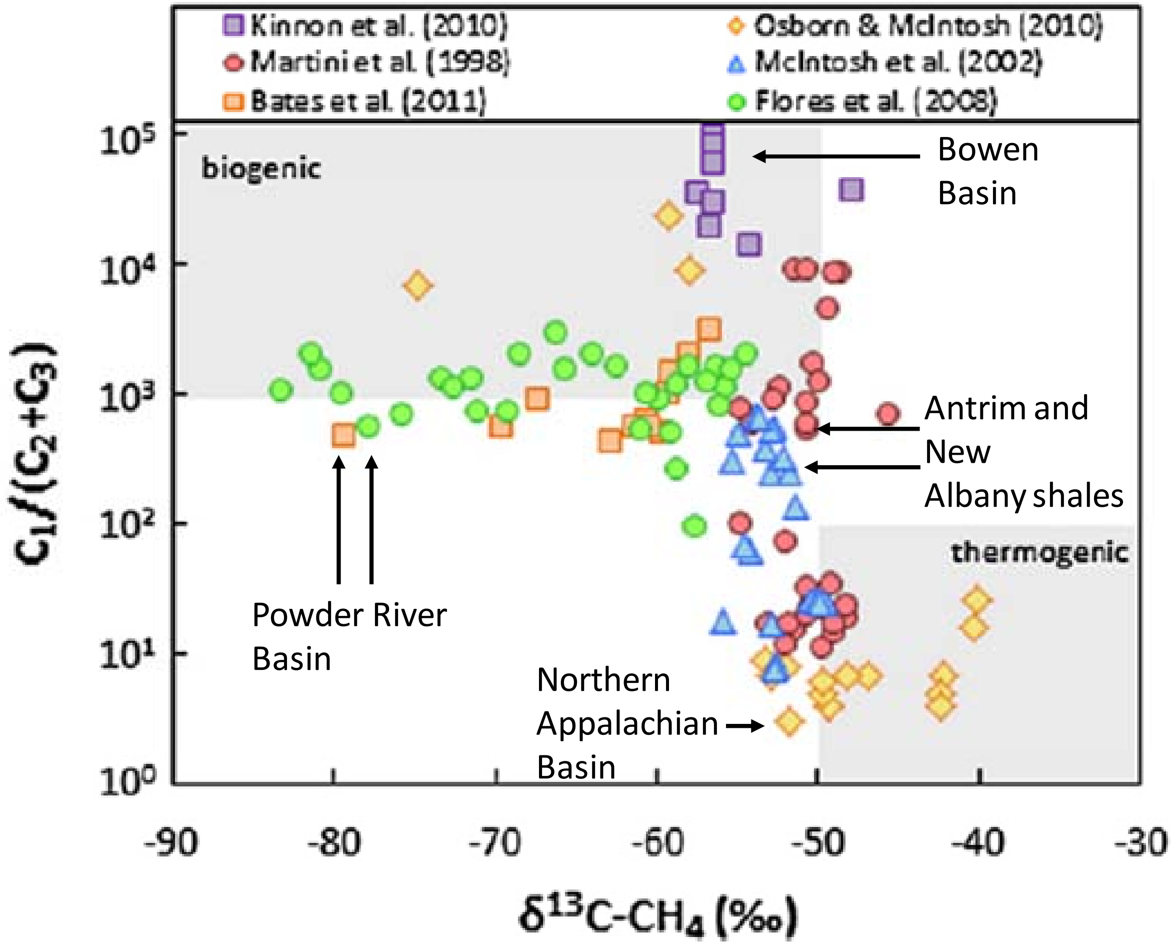

Figure 7 Gas dryness ($C_1/(C_2 + C_3)$) versus δ13C–CH_4 for northern Bowen Basin CSG wells and wells from US basins (Modified from Golding et al., 2013).

Methane will form to some degree if there is coal, but will represent an economically valuable resource only if a sufficient volume of gas is stored and can be produced. Therefore, the coal beds must have formed in an environment with sufficient overlying pressure to prevent gas loss during the coal-forming process. At the same time, in order for the coal layer to act as a gas reservoir, it must have a sufficiently high gas permeability (either natural or induced via hydraulic stimulation) to enable gas movement toward recovery bores. Permeability of coal seam gas reservoirs is due to cleats (natural fractures within the coal) and pore spacing (porosity). Cleats in coal almost always occur as two equally perpendicular sets of fractures. The “face cleat” is the dominant fracture system whereas the “butt cleat” is less laterally continuous and nearly always terminates where it intersects a face cleat (Figure 8).

Coal seam gas recovery is related to the three forms in which it is stored in coal: sorbed in micropores within the coal matrix, as free or dissolved gas (if the gas is saturated) in cleats, and in larger-scale macro-fractures. The pressure of the overlying water and rock keeps the gas in place.

In summary, natural gas sources in the subsurface are varied in nature and strength; the general relationship is that gas sources grade from biogenic to thermogenic with depth. Also, some sources could have associated H_2S, or may tend to have more free gas, rather than low concentrations of dissolved gas.

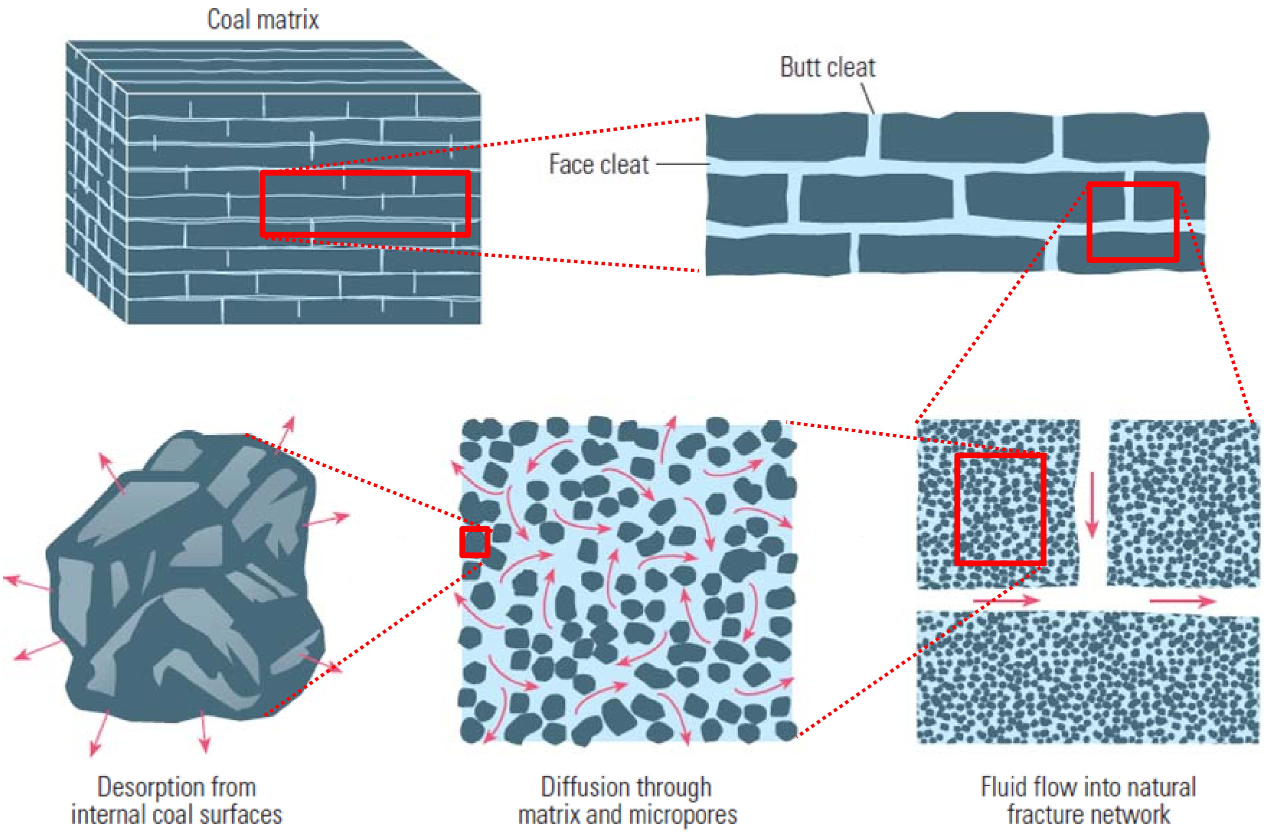

Figure 8 Flow paths through coal with indication of coal cleat orientation. During the initial stage of production, water is produced causing the formation water pressure to decrease allowing liberation of methane adsorbed on the surface of the coal matrix and stored in the micropores. The gas then diffuses through the matrix, migrates into cleats and fractures and eventually flows into the well (Modified from Al-Jubori et al., 2009).

2.4.2 DESORPTION AND DEGASSING

In the context of coal seam gas, an important state of methane is that which is absorbed to rocks and especially coal. The general rule is that as pressure is decreased, and/or temperature is increased, methane will transfer from the adsorbed phase (i.e. desorb), to the dissolved phase (if water is present) and/or to the free-gas phase (i.e. exsolve or de-gas). For the purpose of this report, only pressure changes will be considered, as generally temperature does not play a major role in the migration of methane.

In the case of water-saturated coals, the groundwater must be pumped from a well to decrease the water pressure in the surrounding coal. As the water pressure is decreased, methane desorbs (Figure 9). Desorption of the gas typically occurs at pressures close to atmospheric. This methane first dissolves in water. Because methane solubility in water is limited (about 25 mg/L under atmospheric pressure), the recovery efficiency of dissolved methane is not very high. Efficiency is increased when the water pressure in the well and the formation is decreased sufficiently for methane to exist largely as a free gas phase and to migrate to the production well. This migration involves the movement of both water and gas from the source of methane (i.e. the coal matrix and micro-pores) to the well. These phase transitions occur because the pressure decreases from the coal formation to the pumping well.

However, the pumping for production is not the only way to create the pressure reduction needed for gas to form. Dissolved methane can exist in the groundwater near a water bore. When the water bore is pumped, water pressures in both the bore and the adjacent formation are decreased. Such a decrease in pressure can lead to methane degassing (if the dissolved methane reaches its saturation level at the corresponding pressure) as water is drawn into the bore. Pressure declines due to pumping are exacerbated if the pumping rate is increased or if adjacent water bores start to overlap and interfere with each other or if pumping continues long-term. These declines in pressure could lead to enhanced methane degassing from increasingly larger areas around the bores.

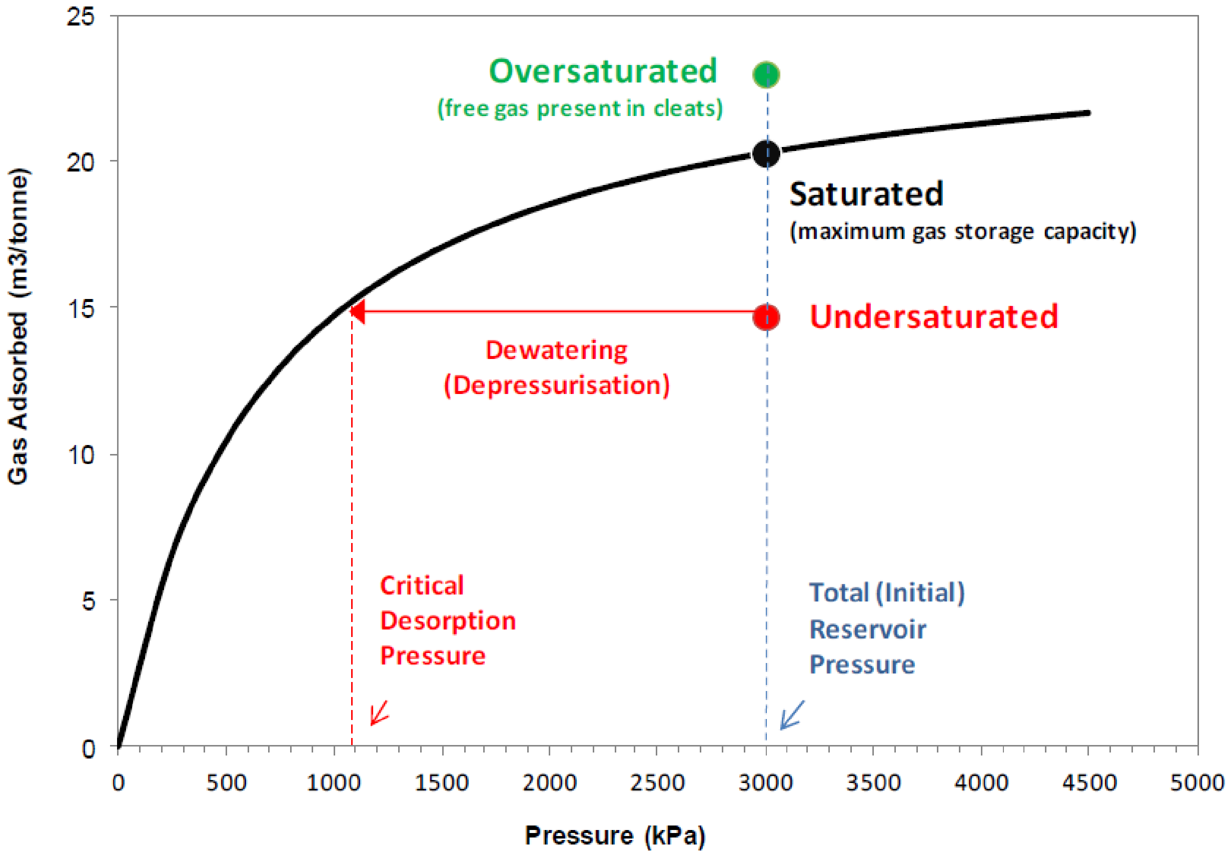

Figure 9 Gas desaturation curve in relation to coal gas saturation (Source: Sydney Catchment Authority, 2012).

Finally, water will undergo a pressure reduction as it moves through the CSG well towards the land surface, resulting in a reduced head of water. This can cause gas release under natural conditions.

2.4.3 TRANSPORT MECHANISMS FOR METHANE

The main transport mechanism for methane in groundwater is by advection. Advection is the movement of the compound (methane in this case) with the bulk fluid phase. Where methane is present in its dissolved form, it will be carried by the water it is dissolved in. The water will move in response to a change in hydraulic gradient (combination of pressure and gravity); the amount of fluid carried is a product of the gradient and the hydraulic conductivity. The hydraulic conductivity represents the ability of the material to transmit water. Larger gaps or fractures within material can conduct larger volumes of water. In general terms, aquitards and cap rocks (e.g. clays and shales) have low conductivities, while aquifers and reservoirs (e.g. sands and sandstones) have high conductivities. Under natural conditions, groundwater will move from recharge or outcropping areas (often higher land) to discharge areas (which could be in the form of springs, streams, ocean and low-lying land). Water will move laterally through aquifers and vertically across aquitards in response to pressure changes (Figure 10).

The main difference between the movement of dissolved gases and free gases is buoyancy. Gases tend to move from high pressure to low pressure but also tend to rise due to buoyancy in water. Advective free gas migration from a point source to the surface can only occur when a continuous free gas phase path is established through an otherwise water-saturated rock matrix. Gas will preferentially invade the largest pore spaces. These have the lowest threshold capillary entry pressures, which makes it easier for gas to enter. Permeable horizontal bedding planes can often have the large pore network necessary for stray gas to migrate both laterally and vertically toward the surface. Highly inclined fractures can also provide a vertical pathway.

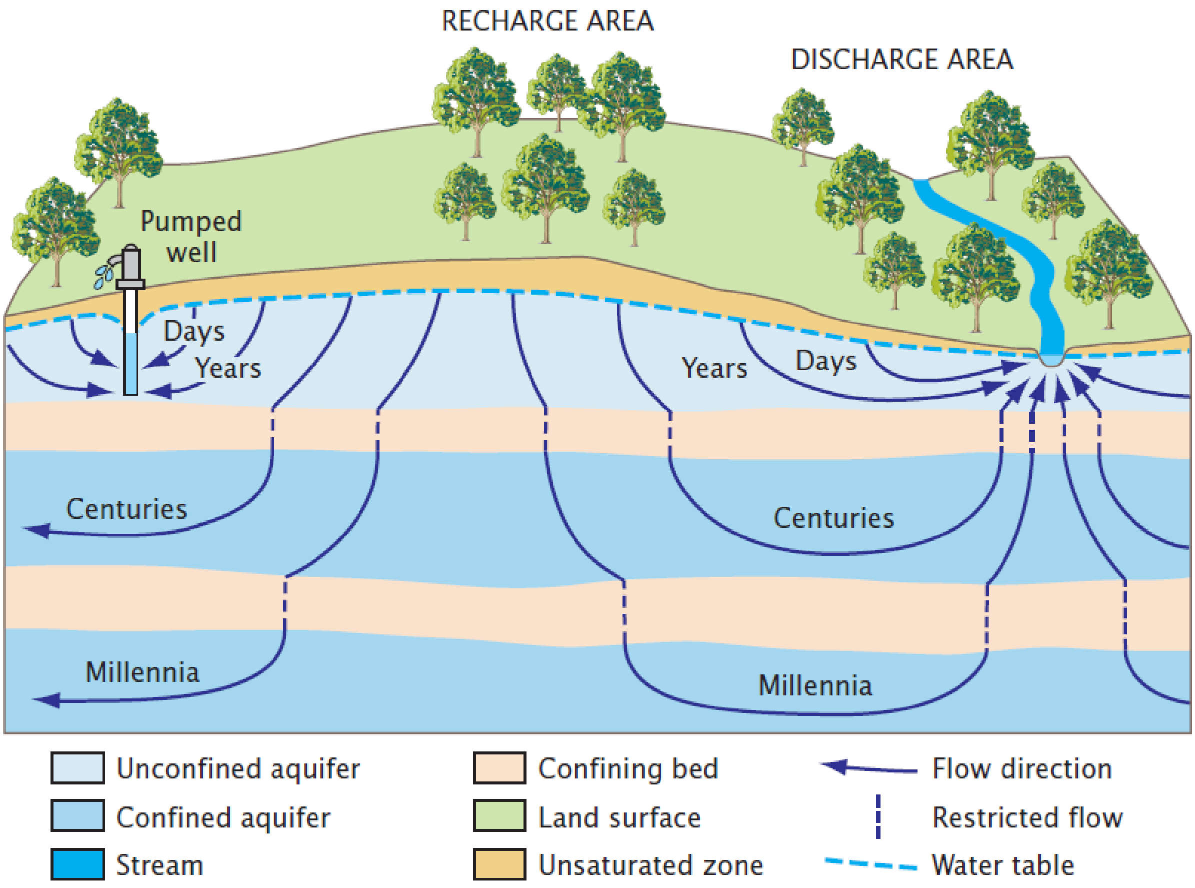

Figure 10 Idealised cross section showing groundwater flow paths from recharge to discharge areas. An unconfined aquifer below the water table flows into a stream. Below that, two confined aquifers are renewed over much longer time scales (Source: CSIRO, 2011).

Rather than gas migration via continuous air pathways, pulsed migration is a dynamic process of free gas movement in pulses through air pathways which intermittently open and close. In pulsed migration, there is a constant competition between capillary forces and gas migrating under pressure through the subsurface. Free gas discharges at the surface in both seeps and affect water bore headspace gas concentrations. The gas breakthrough temporarily releases pressure along the migration path. This allows water to imbibe along the migration path and shut off gas flow. Subsequent pressure build-up at the source then acts to drive water back out of the capillary spaces, re-establishing flow to the surface. Such dynamics can lead to highly variable headspace concentrations of methane. This can lead to pulses of gas in the bore headspace or at least highly variable concentrations. Once the source of gas pressure is mitigated, maximum headspace gas concentration also rapidly declines in a series of pulses.

Depressurisation can lead to gas bubbles migrating to larger pores. This will then block water flow through the larger pores, and reducing the hydraulic conductivity of the aquifer. Thus, an event of gas migration can lead to a reduction of water flow, possibly to water bores.

Advection and buoyancy will lead to the transport of methane from the source of gas to zones of groundwater discharge. In doing so, there can be mixing of water and methane, as pathways coincide. The mixing of water will lead to concentrations of any constituents being between the respective concentrations of the different sources.

2.4.4 METHANE CONSUMPTION

Methane concentrations in groundwater can vary considerably depending on the rate at which it is consumed by bacteria. The domestic bore environment is generally oxidizing, with a strong oxygen gradient between the air-water interface and the bottom of the bore. Due to poor water bore maintenance practices, high concentrations of bacteria can form. These compete for available dissolved or chemically bound oxygen. Many of these bacteria consume methane as a source of carbon to build proteins, and effectively do so at very high rates.

Similarly, when fugitive methane migrates upward along boreholes of oil and gas wells, it may migrate into shallow aquifers or pass through overlying soil to the atmosphere. In a field study near Lloydminster, Alberta, Canada, Van Stempvoort et al. (2005) found hydrogeochemical evidence that such fugitive methane from an oil well had been attenuated by bacterial sulphate reduction under anaerobic conditions. The results supported an interpretation that in situ bacterial oxidation of methane has occurred, linked to bacterial sulphate reduction.

Similar conclusions were made by Gorody et al. (2005) for the San Juan Basin. Available data indicate that anaerobic methane oxidation in the presence of dissolved sulfate ions is the dominant metabolic mechanism in water bore environments. It was also shown that dynamic water bore environmental conditions significantly affect dissolved methane concentrations. Therefore, the amount of residual, oxidized methane present at any given time can be expected to vary significantly, depending on the rate of methane oxidation compared to the rate of fresh methane influx.

2.5 Impact of water, oil and gas development

There are two main ways in which hydrocarbon extraction development has affected the movement of methane. The first is depressurisation that leads to increased gas production and desorption of methane into water. This has been discussed previously.

The second way is by making conduits through the stratigraphic units by water bores or gas production wells. Such borehole breaches present a number of opportunities for leakage of fluids in the vertical direction. Higher heads at depth could transport dissolved gas vertically, while buoyancy effects, and perhaps excess gas pressure, could cause bubbles or stringers of free gas to migrate upwards. Leakage of CO_2 to surface via existing boreholes is the greatest risk to loss of containment in carbon capture and storage monitoring risk registers.

The ability of the fluids to move vertically depends upon the integrity of the borehole. Leakage could occur, for example, through cracking of the cement, cracking or corrosion of the metal casing, poor seals due to poor completion or degradation of materials. The impact of commercial gas operations on natural gas migration from coal seams to the surface can be nearly instantaneous. Buoyancy rapidly drives gas upward through the nearest and largest permeable paths. The free gas phase may migrate up-dip towards the surface along possible pathways including shallow bedding plane boundaries, permeable shallow aquifers, and shallow fractures as well as manmade structures. The USA experience has shown that methane escaping from a problematic commercial oil and gas well is most likely to surface within a 1 km radius of such a point source (Alberta Environment, 2009).

The USA experience has tended to indicate that older bores producing oil and gas from deep conventional reservoirs are more likely to provide gas migration pathways to the surface than shallower and newer coal seam gas wells. For example, in the La Plata County part of the San Juan Basin, approximately 20% of the conventional wells required remedial cement or were plugged and abandoned, while during the same period, approximately 3% of the coalbed gas wells were found to require remedial cementation or were plugged and abandoned (USEPA, 2004). In the Animas River valley groundwater aquifers were contaminated with methane migrating from historic bores that had an uncemented annulus in contact with the Fruitland Formation (Chafin et al., 1993; Chafin, 1994). After leaky point gas sources are remediated, the effect on near-surface gas seepage is also nearly instantaneous. Gas bubbling tends to cease quickly, and areas affected by seeps are rapidly reduced to below detection levels. Declining dissolved gas concentrations in contaminated groundwater plumes, however, may not necessarily be as immediate.

Hydraulic fracturing could also provide preferential conduits for fluid flow. Stimulation of shallow and highly cleated coal seam gas reservoirs often results in horizontal to sub-horizontal fractures that are largely confined to the particular geologic unit (US EPA, 2004). Under some circumstances it might be possible for an induced fracture to propagate as far as an adjacent bore. This is particularly possible where there is a high density of bores. The fracture could then provide a conduit to transmit gases, either as dissolved gas or free-phase gas, between the coal seam gas well and the nearby water bore. There are possible circumstances in which coal seam gas is drawn, through a fracture, to a pumping water bore. This would be limited to situations where water bore and coal seam gas wells are only separated by no more than 200 m.

In a recent review of abandoned wells by the NSW Chief Scientist and Engineer (2014b), reference is made to preliminary results of a collaborative study measuring and comparing methane emissions from various sources including CSG projects and open cut coal mines in NSW and Queensland. At least one abandoned well linked to coal exploration, was found to be emitting methane at concentrations higher than the maximum range of the detection system, at ignitable levels (UNSW, 2014).

2.6 Forensic analyses

The purpose of forensic analyses is to identify causes for any changes to the baseline information target mitigation measures and ensure these measures are working. In some cases, the identification may need to be unambiguous, data defensible and there may be the need to prove that any threat is removed.

An important part of any interpretation is the identification of distinguishing features of the different possible sources of methane. Different types of analytical methods can be used to help determine if a methane gas is of biogenic or thermogenic origin, or a mixture of the two. The analytical methods used to differentiate between the two types of methane are well-known, scientifically accepted, and summarized in Kaplan et al. (1997). Some publications refer to this as ‘fingerprinting’ (Coleman, 1989; Tilley and Muelenbachs, 2012). Generally, sources cannot be characterised in a unique fashion as the name ‘fingerprinting’ suggests. However, isotopic composition of methane is very different dependent on the form of methane formation.

Biogenic gases produced in situ in shallow aquifers are predominantly composed of CH_4 with low $\delta^{13}C$ (−50 to −110‰ VPDB) (Figure 7) and $\delta^{2}H$ values (as low as −350‰ VSMOW). In contrast, thermogenic gases generated at elevated pressures and temperatures are usually composed of methane (CH_4, abbreviated as C_1) and higher alkanes, especially ethane (C_2H_6, abbreviated as C_2) with $\delta^{13}C$ values often ranging between −55 and −25‰. ''dryness'' (often estimated as the ratio $C_1/(C_2+C_3+..)$) is used to characterise natural gas (Golding et al., 2013). For biogenic gas, the dryness is typically more than 1000 and for thermogenic gas is less than 1000 (Figure 7). These are usually visualised using a Schoell diagram (a plot of ^2H in methane against ^{13}C in methane) and a Bernard diagram (a plot of wetness against ^{13}C in methane). Stable isotope analyses and dryness parameters when used together and visualised through the use of Schoell and Bernard diagrams can be an effective tool to assess the sources of natural gas in shallow aquifers.

The characteristics of the various methane sources can be variable. Large differences between point source gas compositions can occur if source gases invading the shallow groundwater environment are derived from mixtures. It is important to characterise all sources. Also, produced gas samples can have variable isotopic compositions when the completion interval is long. A particularly important source required for the isotopic fingerprinting of gas-bearing formations is the characterisation of $\delta^{13}C$ values of gases in drilling muds recovered from the vertical portion of energy wells (Jackson et al., 2013).

Methane can migrate from thermogenic sources over long periods of time and pervade various formations. Hence, the methane in each formation may be a mixture from different sources. As part of the baseline survey, it would be important to characterise locally the chemical and isotopic compositions of natural gas in all gas-bearing formations. It may also be possible to identify the formation from which gases in water bores have been derived.

The approach in any forensic analysis is to sample potential gas sources within a certain radius of influence and to compare them with monitoring data of free and dissolved gases from affected water bores in baseline and subsequent surveys. If there is good contact between a source of natural gas and a gas seep, then the stable isotopic composition of the free gas phase at the seep tends to correspond precisely to that of the source.

When methane occurs in the dissolved phase, the composition is likely to be affected by the processes occurring during transport such as dilution, mixing and consumption. There are long-established methods for investigating mixing and dilution using hydrochemical methods. Direct mixing between two sources shows up as a straight line when two constituents are plotted against each other with the ends of the straight line representing end-members. It is important to note that direct mixing between two end members is not very common and where it is assumed it is probably often an oversimplification. Emphasis is placed on finding constituents which distinguish different sources. Dilution is also distinguished by ratios of constituents being constant, generally a conservative tracer such as chloride as the denominator.

Consumption requires measurements directly relevant to this process. The chemical effects of bacterially-mediated aerobic and anaerobic methane oxidation can be readily observed on the basis of stable isotope ratios for carbon in methane and dissolved carbon dioxide, and deuterium in methane. Bacteria preferentially consume methane with the more depleted (lighter) isotopes. Accordingly, bacterially-mediated methane consumption leaves a residual pool of dissolved methane enriched in heavy isotopes. Bacterial respiration, on the other hand, generates a dissolved carbon dioxide pool which becomes correspondingly depleted in heavier isotopes. If bacterial methane consumption rates are higher than the rate at which dissolved methane is introduced into a water bore, then methane concentration will decrease, the stable isotopes of residual methane will become enriched in the heavier isotopes, and the stable carbon isotopes in dissolved inorganic carbon will become increasingly depleted. The opposite becomes true if the rate at which methane is introduced into a bore outpaces the ability of bacteria to consume it. Temporal analyses of stable isotopes in methane and dissolved inorganic carbon from water in a bore are necessary to document either variable source methane mixing dynamics or increasing methane concentrations resulting from a contaminant plume (Gorody et al., 2005).

To reduce costs and focus effort on problems, a monitoring strategy needs to be tiered. This could be initially on the basis of whether methane is biogenic or whether there is a threshold value of methane. Initially monitoring should test isotopic composition of methane, other hydrochemical indicators as well as methane and should characterise methane sources and water in bores near production wells. This characterisation should include spatial and temporal variability. Subsequent testing may then focus on bores with thermogenic or mixed methane and where methane concentrations are above a threshold. Where the methane concentration is increasing or if the methane concentration is sufficiently high, a forensic analysis should be considered.

2.6.1 THE SAN JUAN EXAMPLE

Perhaps the best illustration of the power of a well-constructed and tiered baseline survey is that of the San Juan valley, Colorado (COGCC, 2003; Gorody et al., 2005). In 2000, the Colorado Oil and Gas Conservation Commission (COGCC) mandated testing of groundwater bores prior to and following drilling additional wells in the Fruitland Formation. As a condition for obtaining a drilling permit, operators are required to sample the two closest domestic groundwater bores within a 900 m radius of each planned well in the Fruitland Formation. If dissolved methane is detected in a concentration exceeding 2 mg/L, chromatographic analysis of the gas and carbon isotopic analysis of methane carbon is required to determine gas type (thermogenic, biogenic, or a mix of both). If test results reveal biogenic gas, no further isotopic testing is necessary. If the carbon isotope tests result in a thermogenic or mixed signature, annual testing is required. If the methane concentration level increases by more than 5 mg/L between sampling periods, or if the concentration increases to more than 10 mg/L, the operator responsible for testing must submit an action plan to determine the gas source.

As of 2004, over 2000 data records containing measurements of dissolved methane concentrations in groundwater were available in the COGCC database. Groundwater samples had been collected from over 1000 different water bores. Of those, there were 589 sites with multiple water quality analyses. Dissolved methane was measurable at 65% of all bores sampled (Gorody et al., 2005).

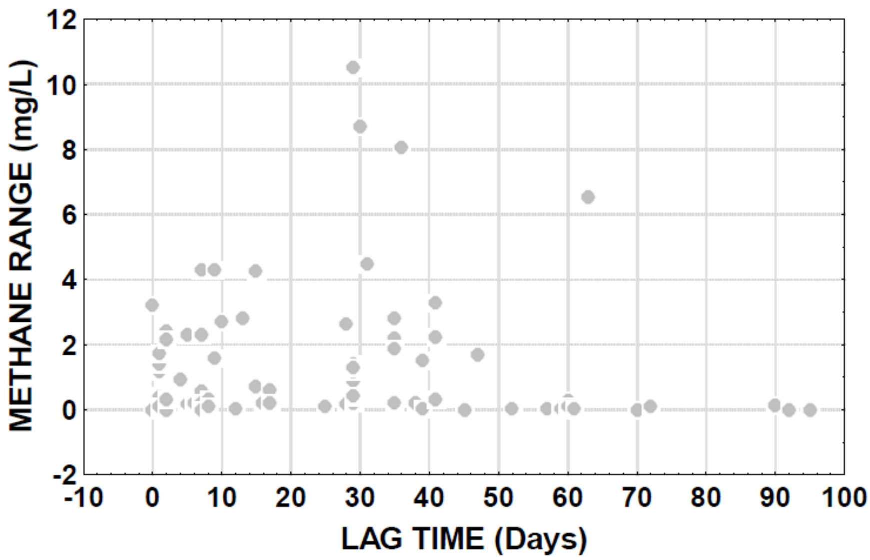

Figure 11 Difference between minimum and maximum methane concentrations in water bores sampled multiple times within a period of 95 days (Source: Gorody et al., 2005).

Multiple data sets from individual water bores also allowed the COGCC to evaluate in detail the factors that influence dissolved methane concentrations in groundwater (Gorody et al., 2005). The COGCC's study showed that methane concentrations in selected bores with multiple sampling results collected within a sampling period of 95 days was variable (Figure 11). It showed that maximum values (MaxC1) differed from minimum (MinC1) values by a factor of 1.14×MinC1 + 0.55 mg/L (Gorody et al., 2005). The long term variability between the minimum and maximum dissolved methane concentration among multiple samples collected at 397 water bore sites in the San Juan Basin exhibited an average variability of +/- 54%. Of 292 sample pairs of water bore samples collected prior to and after drilling, 113 sample pairs had detectable levels of dissolved methane at least once; of those, 52 (46%) had post-drilling methane concentrations that were not lower than pre-drilling values; of those, 14 had post-drilling methane concentrations that were both greater than pre-drilling values and that exceeded the expected variability over the short term; of those, only 10 of the 14 water bores sampled in consecutive years contained more than 2 mg/L dissolved methane; of those, 8 contained biogenic methane. The remaining 2 sites contained methane with stable carbon isotope measurements of thermogenic origin. Detailed analysis of the data from both remaining sites with dissolved thermogenic methane demonstrated that the observed increase in post-drilling methane concentration was not due to drilling new Fruitland wells (Figure 12). Among the several causes for increased methane concentration, a decrease in Na_2SO_4 type fluids available to dilute methane bearing NaCl type waters was reported.

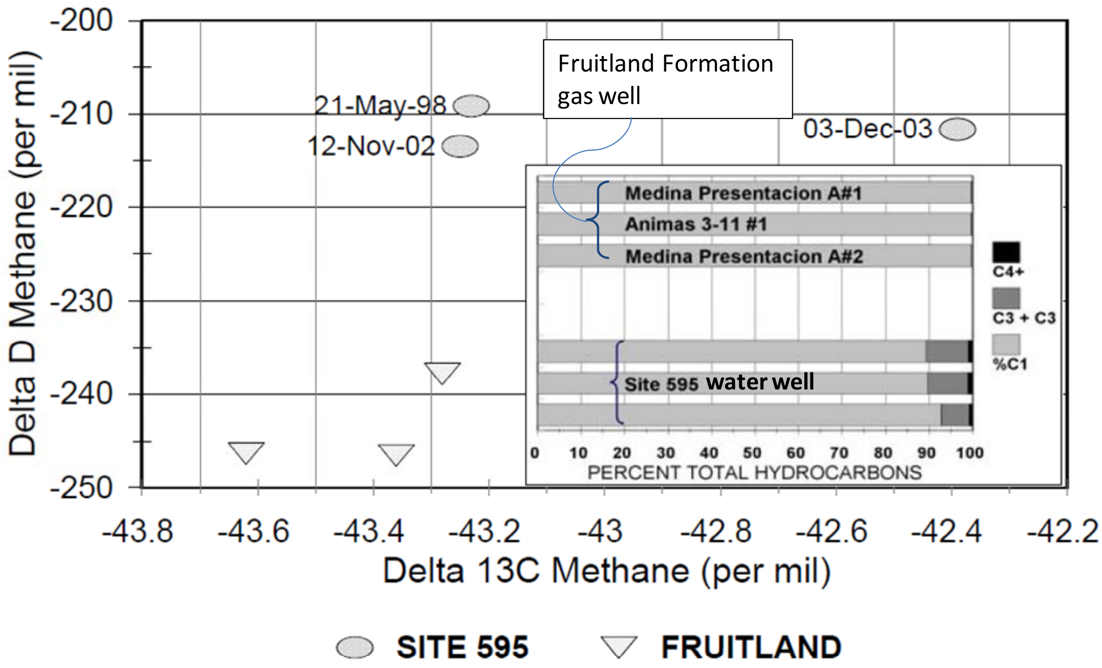

Figure 12 The dissolved gas composition (inset) and the stable isotope composition of methane at site 595 (water bore) methane does not correspond to that in the underlying Fruitland Formation gas. C1 = methane, C2 = ethane, C3 = propane, C4 = butane (Modified from Gorody et al., 2005).

In the San Juan valley the two principal environmental factors controlling methane concentrations in water bores are (Gorody et al., 2005):

- There are numerous, vertically stratified, confined and unconfined aquifers at all locations in the basin. There are four main water types in the basin, which can be described on the basis of major ion chemistry. Most water bores appear to tap more than one of these aquifers even though they may be screened across thin completion intervals. Depending on the relative contribution of water to a bore from any of these layered aquifers at any given time, dissolved methane originating in water from one aquifer can be variably diluted. Alternatively, dissolved methane of different origins can become variably mixed depending on the relative contribution and mixing rates of different aquifer fluids in a water bore; and

- Due to poor water bore maintenance practices, the overwhelming majority of water bores in the basin have been documented to contain in excess of 1 million colony-forming units of bacteria per mL of water. This has led to bacterially-mediated methane consumption of methane, further contributing to methane variability in addition to the variability owing to presence of multiple aquifers with different characteristics.

3 Occurrence of gas in Surat and Bowen basins

3.1 Introduction

The objective of this section is to collate readily available information in relation to gas in water bores prior to CSG developments in the Surat and Bowen basins in Queensland. A historical perspective is important to build up the baseline information, with which to measure subsequent impacts. As with all coal seam gas basins, methane gas has always been present in both shallow and deeper layers in the Surat and Bowen basins (DNRM, 2013). As can be seen through the press clippings (see Historical media reports section 3.2), presence of methane gas has become more apparent as exploration for water, oil and gas has occurred. Not only does the exploration expose the presence of methane during drilling, making its presence more obvious, but the construction of bores potentially provides conduits for methane migration. The subsequent development of these resources leads to potential depressurisation of the aquifers causing gas to desorb from coal surfaces and to exsolve from the water, potentially making methane occurrences more frequent.

Methane will move naturally to the surface through either advection with water or buoyancy. Pathways can be natural, especially through fractures and faults or through man-made conduits such as bores. Natural discharge of methane can then be found at the surface as micro-seeps, bubbles in streams and wetlands or emissions to the atmosphere. Surveys conducted on micro-seepage areas prior to CSG development will be briefly discussed in this section. Although not directly linked to groundwater, such measurement is evidence of gas migrating to the surface and provides clues as to the spatial and temporal pattern of gas in the unsaturated layer. Increased presence of such areas can be a sign of emerging problems with water bores.

The records of drillers are an important first clue to the expression of free gas in water. Not only should drillers be recording presence of gas, but some of the more significant events are likely to have been recorded in the press. While this report also covers evaluations of drilling logs, the section below reports on press clippings and some analyses based around drilling logs.

As groundwater enters the bore under pressure, it can degas. Harris et al. (2012) reports on ”Anecdotal evidence from landowners includes references to ‘gassy’ bores, ‘burping’ bores, flaring bores and rumours of lighting farmhouses from the gas produced from the water bore. Further evidence is provided from the need to replace bore pumps due to the motors burning out as a result of cavitation when the dissolved gas comes out of solution.”

This section will then describe:

1. Historical media or reports related to the topic;
2. Any collated data on gas in bores or during drilling; and
3. Studies on land surface seepage areas.

3.2 Historical media reports

Within this section, we extract some key quotes from media related to the topic. The use of quotes is deliberate as any conversion of the words will inevitably invoke a bias, in this case, to what we understand is the science and what we understand in hindsight.

3.2.1 ROMA 1900 - 1908:

Courier Mail (Brisbane) May 26, 2001[4]:" Since Roma had been gazetted in 1862 as a centre to serve the rich pastoral runs around it, they had been desperately searching for water, the more so since the railway, with its thirsty steam locomotives, had arrived in 1880".

"At Roma in 1900, natural gas blew into a water bore at 1123 metres."

Courier Mail (Brisbane) May 26, 2001: "AT FIRST there was just a rumble -- more of a burp, really -- from deep beneath a little rise somewhat extravagantly known as Hospital Hill. Then, at 1.15pm on October 16, 1900, the wellhead exploded, sending water and mud about 15m into the air above the small collection of stores and shacks known as Roma. Cheering around the drilling derrick soon subsided. Townspeople's noses wrinkled as much in disappointment as distaste. ...Now the air was filled with the stink of natural gas, the water subsiding to little more than a trickle. The government hydraulic engineer pronounced it "swamp gas", good for nothing. It did not occur to anyone that this could be the first indication of vast fossil fuel reserves beneath Australia's wide brown crust."

The Brisbane Courier (Brisbane), Saturday 8 December 1900, page 11: "The Water Supply Department intended to take measures to separate the gas from the water, and convert the flow from the two bores into one flow, which will be available for the use of the townspeople. If the efforts to be made to secure the gas be successful, it will be possible, it is hoped, to use it for illuminating purposes, which will be incalculable advantage to Roma. The idea, so far as it can be surmised, is to put a pipe down inside the casing to a spot below the stratum, which now furnishes the water, so as to intercept the gas, and thereby conduct it to the surface through the pipe in the water. Once this is successfully accomplished, it will be easy to connect the pipe with a gasometer, and from that storage, the gas can be conveyed to any part of the town."

Courier Mail (Brisbane) May 26, 2001: "After that first strike, for instance, Roma and the state government squabbled for six years before deciding to light up the town with natural gas lamps and fittings. Came the big day and Roma dazzled its citizens and wildlife alike with brilliant light until, 15 days later, the gas ran out. It had been allowed to gush freely into the atmosphere for those six years".

Figure 13 shows a picture of an apparatus for separating natural gas from artesian water.

3.2.2 ROME BORE 1908

Western Star and Roma Advertiser (Toowoomba), Wednesday 28 October 1908, page 2: "When the man in charge of the shift noticed that the water was gradually rising over the casing. Then he noticed that the water had become less in volume and was impregnated with air or gas...when suddenly the beam bearing the weight shot up , and an immense volume of gas rushed from the mouth of the casing with a terrific roar...Perhaps for a quarter of an hour it continued thus, when suddenly , with an explosion similar to the discharge of a canon, the gas was converted to flames... the flame shot up to a height of 40 feet or more and none could nearer to it than 50 yards, so intense was the heat...The flames consumed everything , and including the engines...It was remarkable that the immense flames were for a long time unaccompanied by smoke, but in a few hours, the flames were discoloured by black smoke, and the fierceness with which they

[4] http://www.energyandresources.vic.gov.au/earth-resources/geology-of-victoria/exhibitions/history

roared was greatly intensified. The change was attributed to the presence of petroleum in large quantities...The first and only thing to be done now is to find a method of extinguishing the fire.”

Figure 13 Apparatus for separating natural gas from artesian water at the Roma Gas Works, Queensland, ca. 1906 (Source: State Library of Queensland, John Oxley Library, -26.573429, 148.787323)

Cairns Morning Post (Cairns), Friday 30 October 1908, page 5: “He attributed the outbreak to the wind driving the gas out of the fire under the boiler....Mr Taylor said that kerosene in abundance was coming from the bore”.

Courier Mail (Brisbane) May 26, 2001, Saturday: “The year 1908 saw the beginning of Roma's tourist industry. People from hundreds of kilometres around arrived by train, car, horseback or buggy to see a huge gas fire caused when a drilling operation, financed in part by the Queensland government, allowed escaping gas to be ignited by a steam boiler. The blaze lasted 46 days. Three years later the operating company went broke although the well remains a source of water for the town.”

3.2.3 SEARCH FOR OIL IN QUEENSLAND FROM 1908 TO 1960’S (1908-1960)

Sydney Morning Herald (Sydney) March 8, 1988 Tuesday: “During the early 1900s, several eminent geologists believed Australia too old, geologically speaking, to have formed substantial oil or gas deposits. Others preferred to believe their eyes and mounted extensive drilling campaigns based on the occurrence of true seeps and inflows of oil and gas into water bores, particularly around Roma,”

Courier Mail (Brisbane) May 26, 2001;” With the motor car beginning to dominate private transportation, the 1920s saw an "oil boom" – something like 46 companies and fortune-seeking American drillers sinking holes all over the countryside. One of them brought in large quantities of light oil which, refined locally, was sold during the Great Depression as Roma petrol “.

The Northern Miner (Charters Towers), Saturday 13 November 1920, page 3: "The recent blow of gas at Roma has once more awakened interest in the possibilities of obtaining petroleum in Australia. The gas was induced to flow by lowering the head of water in the bore. The bore had been drilled 'wet', that is it was kept full of water, and when the American driller who was in charge struck the gas rock he reported it as a "small gas show". ..The pressure in pounds per square inch due to the water column in a bore is found by measuring the depth in feet and multiplying by 0.434 which is the weight in pounds of a column of pure water one square inch in section and one foot high, as that, taking the Roma bore, with a depth of 3700 feet we get a result of 3700 x0.434 per sq inch on the bottom of the bore. In order to overcome this pressure, and force the water up out of the bore, the gas pressure would need to be higher. The water level was lowered a few hundred feet at Roma, and the back pressure on the gas was thereby reduced to such an extent that the gas blew out"

The Western Champion (Barcaldine), Saturday 11 March 1922, page 17: "Dr H. I. Jensen, a geologist in the Mines department,... provided an interim report on leases ..20 miles west of Tambo... that no appreciable amount of oil has been found in boring for artesian water strongly discounted the chances of getting oil in payable quantities in the marine cretaceous".

The Western Champion (Barcaldine), Saturday 2 August 1924, page 16: "Turning to the evidence of petroleum. These are generally displayed in the form an evolution of inflammable gas, or the presence of an oily film on the surface of the water. This direct contains many evidences of this nature in the form of discharges of gas from artesian and sub-artesian wells... gas issuing with water ..certain proportion of liquid petrol in suspension..paraffin wax has been coming up.. appreciable discharge of inflammable gas. .. it must be remembered that ...a bore 3000 feet deep would have a pressure of roughly 1500 pounds to the square inch on the bottom.. if the water was excluded, and the bore bailed dry, the gas would come out in enormous quantities, at a pressure over 1000 pounds per square inch. .. this writer hopes to see at no distant date, some use made of this cheapest and best of nature's fuels, .."

Western Star and Roma Advertiser (Toowoomba), Wednesday 21 October 1925, page 1. "the evidence to date suggests there is still quite a possibility of tapping low-pressure oilbeds in either Roma or the Longreach-Windorah area, but the methods at present used in boring for water would tend to drown out any low-pressure reservoirs of gas or oil".

The Longreach Leader (Longreach), Friday 29 July 1927, page 30: "Mr J.W.Booker who was working on the Westland artesian bore... submitted to the Department of Mines several samples of oil indications for analysis ..Two samples were taken by submerges and displacement but the Government analyst's report dispelled any hope of its being petroliferous- the results were .. methane 89.1 percent and 87.4 percent.."

The Brisbane Courier (Brisbane), Thursday 13 September 1928, page 16: "The head driller ..has fixed a contrivance on the town bore which supplies the town with water, giving greater freedom for the gas to escape. When ignited, there is a continuous flame 5ft. or 6 ft. high".

The Queenslander (Brisbane), Thursday 19 September 1929, page 62:" In an interview with Dr H. I.. Jensen.. That the Walloons are the source of the oil manifestations at Roma is more than likely, because of the presence of traces of oil in many horizons of the upper, middle and lower Walloons, the wide gas development in pockets, .."

The Longreach Leader (Longreach), Friday 17 October 1930, page 10;" Water bore at Mitchell: A rush of gas, which immediately caught fire, was encountered during well-boring"

The Charleville Times (Brisbane), Friday 9 January 1931, page 10: "When the owners of Ruthven were notified of the oil in the bore sunk for water, they order the contractor to case it out and go on for water...

Sheep won't drink oil; it's water we want ...about ten miles east of St George. The natural gas met with at Eromanga is a pure methane gas."

The Charleville Times (Brisbane), Friday 23 January 1931, page 10: "The natural gas from Eromanga is 96.4 percent methane... Natural gas migrates more easily than liquid hydrocarbons. Where there are no water troubles, a well drilled to the upper surface of the oil sands, the release of pressure is so great, and causes readjustment of equilibrium between the various hydrocarbons that the simpler and lighter compounds, chiefly, gaseous, enter the well in great and increasing quantity before any oil, except perhaps for the merest light filtrate, can reach the bore. This may take place, before the oil-bearing sands are actually tapped, as was the case in the Roma bore"

Townsville Daily Bulletin (Townsville), Friday 15 June 1934, page 12;" The men employed by the Collinsville Colliery Company resumed work on the mine at Scottsville on Tuesday last week. Operations are to be confined to those parts of the property accounted free from any suspicion of deleterious gas emanations until adequate means are adopted to guard against any possible harmful results in exploiting other sections of the coal seam."

The Courier-Mail (Brisbane), Friday 16 June 1944, page 4: "Analysis of gas from a sub-artesian bore in the Chinchilla district shows that it is of a much higher value than ordinary domestic coal gas".

The Courier-Mail (Brisbane), Wednesday 15 November 1944, page 6;"Mr Gair said inflammable gas given off by the shallow coal seams in the Chinchilla district was rather irregular and there was no evidence that the volume reached normal commercial requirements, although it was understood to have been used to drive a small internal combustion engine."

The Central Queensland Herald (Rockhampton), Thursday 20 March 1952, page 4: "An old oil bore eight miles from Roma broke a nine-ton concrete seal this morning and hurled a column of gas and water 120 feet into the air".

The Courier Mail (Brisbane) March 8, 2008 Saturday: A little over 55 years ago four men drilling for water near Chinchilla sparked an explosion that reverberated around the world. They didn't know it at the time but they had spiked a massive methane gas chamber trapped inside an underground coal seam. When one of the men lit a cigarette, the blast sent them flying through the air. The Brisbane Telegraph reported that a 15m flame burned for weeks before a crack team of mining engineers from the US was able to cap it.

Morning Bulletin (Rockhampton), Saturday 9 January 1954, page 4: "drillers and boring inspectors had found gas and oil or wax with a flow water in numerous bores in the Surat Basin near Tambo and along the northern and western margin of the Eromanga Basin".

3.2.4 POST 1960'S

The Associated group discovered gas in 1960 at Timbury Hills-1 near Roma in the Surat Basin. It took until 1969 before that gas flowed by pipeline to Brisbane. However, in 1961, a joint venture of AOG, union Oil and kern County Land, drilled Cabawin-1 in the same area and flowed oil at 80 bopd. Although not commercial, this discovery provided encouragement for the JV to drill Moonie-1. Moonie-1 flowed oil and water at 500 bopd and was to be Australia's first commercial field."[5]

Sydney Morning Herald (Sydney) March 8, 1988 Tuesday: "Nevertheless, the doubters were finally disarmed by the fabulous run of discoveries in the 1960s, beginning with gas at Roma and oil at Moonie and

[5] http://www.energyandresources.vic.gov.au/earth-resources/geology-of-victoria/exhibitions/history

ending with both oil and gas in Bass Strait. Suddenly, Australia had earned a place among the international oil producers and the term "self-sufficiency" was heard for the first time. Nevertheless, the search is continuing and discoveries are still being recorded in regions such as the Eromanga Basin of Queensland and the Timor Sea. ..”

Courier Mail (Brisbane) May 26, 2001, Saturday : “The post-World War II era saw a revival of the search for gas but it was not until 1969 that sufficient reserves were found in the Cooper Basin to warrant a pipeline to Brisbane and Gladstone.”

3.3 State reports

In this section, we describe state reports relevant to the topic.

Gray (1967) reported on an investigation of an incident in which gas blew out from a water bore drilled near Brigalow on the eastern flank of the Surat Basin. The blowout reached a maximum height of 30 feet and lasted for approximately 40 hours before dying out.

DNRM (2011) reported on a number of occurrences of gas in water bores within 5 km of the Davis property, 15 km south of Chinchilla, prior to coal seam gas development. “Anecdotal records of gas in bores in this particular area date back to 1916. In the GSQ Publication Number 299, Occurrence of Petroleum and Natural Gas in Queensland, 1960, Brown's Scout Bores numbers 1 and 2 (now referred to as RN 22020) were drilled in 1929 to "investigate the possibility of petroleum in the area", as "gas under pressure had been reported from a water bore on the same portion in 1916" (page 18). A copy of this page of the publication is included on water licence file TMB/515/004(2353). Number 1 struck a small quantity of gas ... and number 2 struck a better gas show ... Further evidence of gas in water bores is summarised in Table 1.

Figure 14 shows a map of the occurrences of Petroleum and Natural Gas in QLD as of 1960 (Geological Survey of QLD, 1960). This map was compiled by the Geological Survey of QLD and the QLD Department of Mines. This map extends beyond the Surat and Bowen basins, but does show many sites within this area.

Table 1 Evidence of gas in water bores (DNRM, 2011).

Bore #	Date drilled	Evidence of gas
RN 8642	1938	Gas was evident in the bore by 1966, but it is not known how early gas was blowing from the bore
RN 10790	1946	In a letter to the department, the licensee noted that the bore started blowing gas in 1960
RN 24465	1946	Gas was evident in the bore by 1966, but only in very humid weather
RN 13600	1958	Gas was evident in the bore at the time of drilling
RN 14042	1958	Gas was evident in the bore at the time of drilling
RN 48528	1966	On a renewal dated 1996, the licensee noted that the renewal was not required as the bore produced too much gas
RN 24485	1966	Gas was evident in the bore later that same year, but it is not known if it was evident at the time of drilling
RN 33553	1969	Gas was evident in the bore at the time of drilling
RN38191	1971	Gas was evident in the bore at the time of drilling
RN 107762	2001	Gas was evident in the bore at the time of drilling

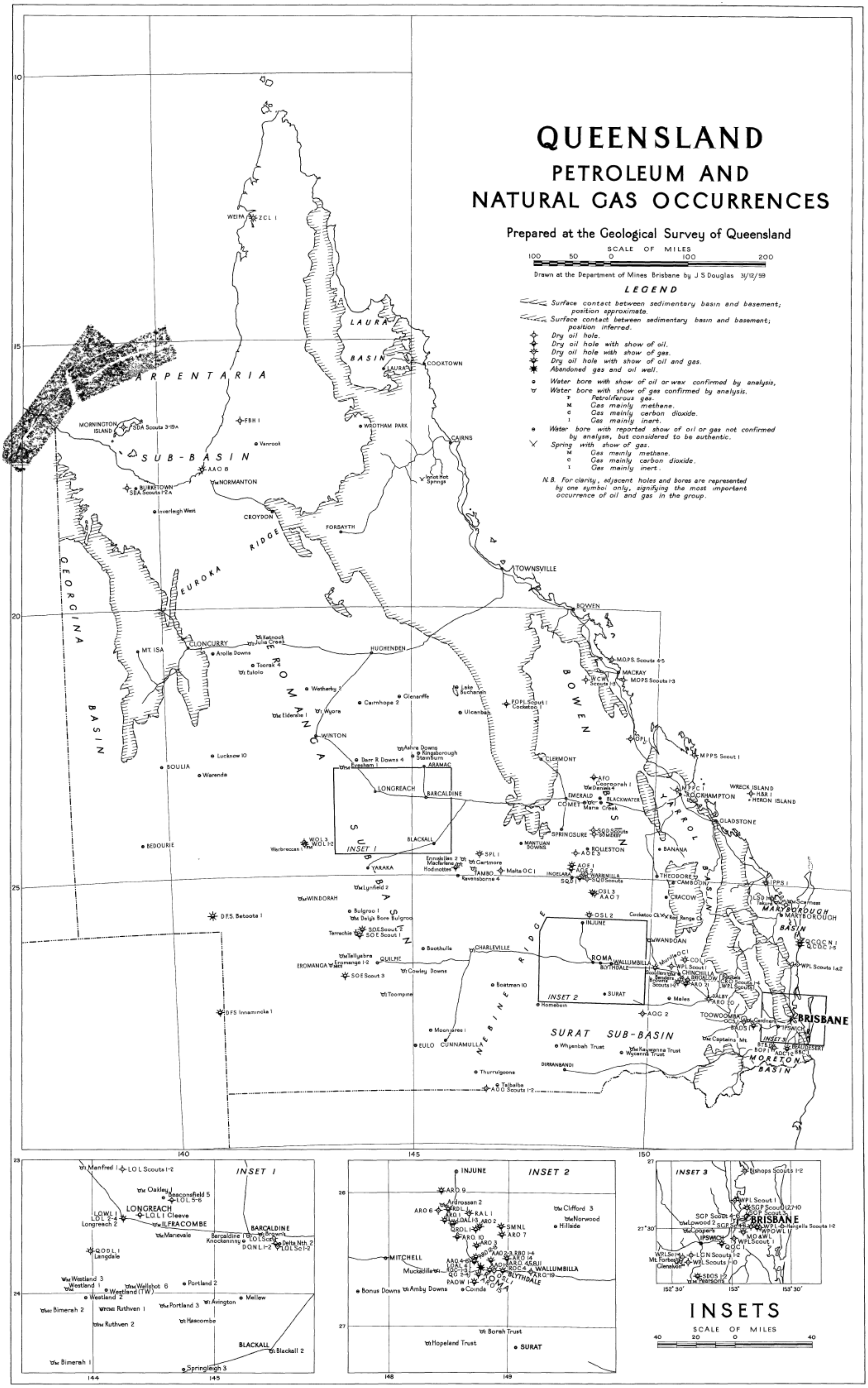

Figure 14 Occurrences of petroleum and natural gas in Queensland (Source: Geological Survey of Queensland, 1960)

3.4 Micro-seeps

Methane gas seepage refers to the diffusive flux of methane to the atmosphere through the land surface and water bodies, the localised flux of methane via connected pathways consisting of leads, faults and outcrops and the flux from agricultural bores. Seepage does not consider the fugitive emissions of methane occurring as part of open cut and underground coal mines or emissions occurring from infrastructure (wells, compressors, associated water reticulation, or gas pipelines) associated with coal seam gas production. A comprehensive review and analysis of literature on methane detection and flux determination is provided in Day et al. (2013). The review is part of a Gas Industry Social and Environmental Research Alliance (GISERA) project addressing the location and quantity of background methane emissions in the Surat Basin, Queensland, Australia.

Micro-seepage areas are often naturally occurring parts of the land surface, where methane escapes to the atmosphere. Generally, methane reserves would diminish over geological time, if much methane escaped to the surface through low permeability layers. Nonetheless, some gas is always likely to escape. This is likely to occur through fractures, faults or through up-trending or outcropping geological zones.

As new pathways are created or as depressurisation leads to increased fluxes, it might be expected that new seepage areas are created and that old ones may move or increase. Where there is a change, it is possible that this may become a risk to infrastructure including water bores, as seen in San Juan valley in the US, including water bores. Soil surveys can prove to be informative about the fluxes of methane through such seeps.

Historically, gas surveys have been conducted to provide information about possible production sites. The underlying principle for this method goes back nearly eighty years. It assumes that there is a migration pathway from a source of gas most likely by micro-bubbles going through micro-fractures driven by buoyancy forces. The method also relies on anomalous measurements against the broader background on the belief these were associated with reservoirs and migration pathways.

DNRM (2013) reports on 13 soil gas surveys within the Surat Basin. These soil gas surveys have been sampled below surface at depths down to 2 m. In many investigations hundreds of samples were collected. Many of these studies tested for other light alkanes – ethane, propane and butane. A few investigations measured above ground gas concentrations, using a helicopter flying at 5 to 10 m above ground surface, providing qualitative measurements. In some cases, they were able to correlate anomalies with faults and low measurements with wet weather (saturated soil).

Methane seeps may be distributed over very large areas of covering thousands of square kilometres and consequently some method of surveying a region is required for detecting the presence of individual seeps. One method is to use a vehicle fitted with a methane analyser (an Apogee leak detection system based on an infrared spectrometer) to detect elevated ambient concentrations of methane. When higher levels of methane are found, the source can be traced and other methods such as soil gas analyses and flux chambers can be used to characterise the seep. Figure 15 shows an application in Queensland where a vehicle is driven through the plume to measure ground level methane concentrations (Day et al., 2013).

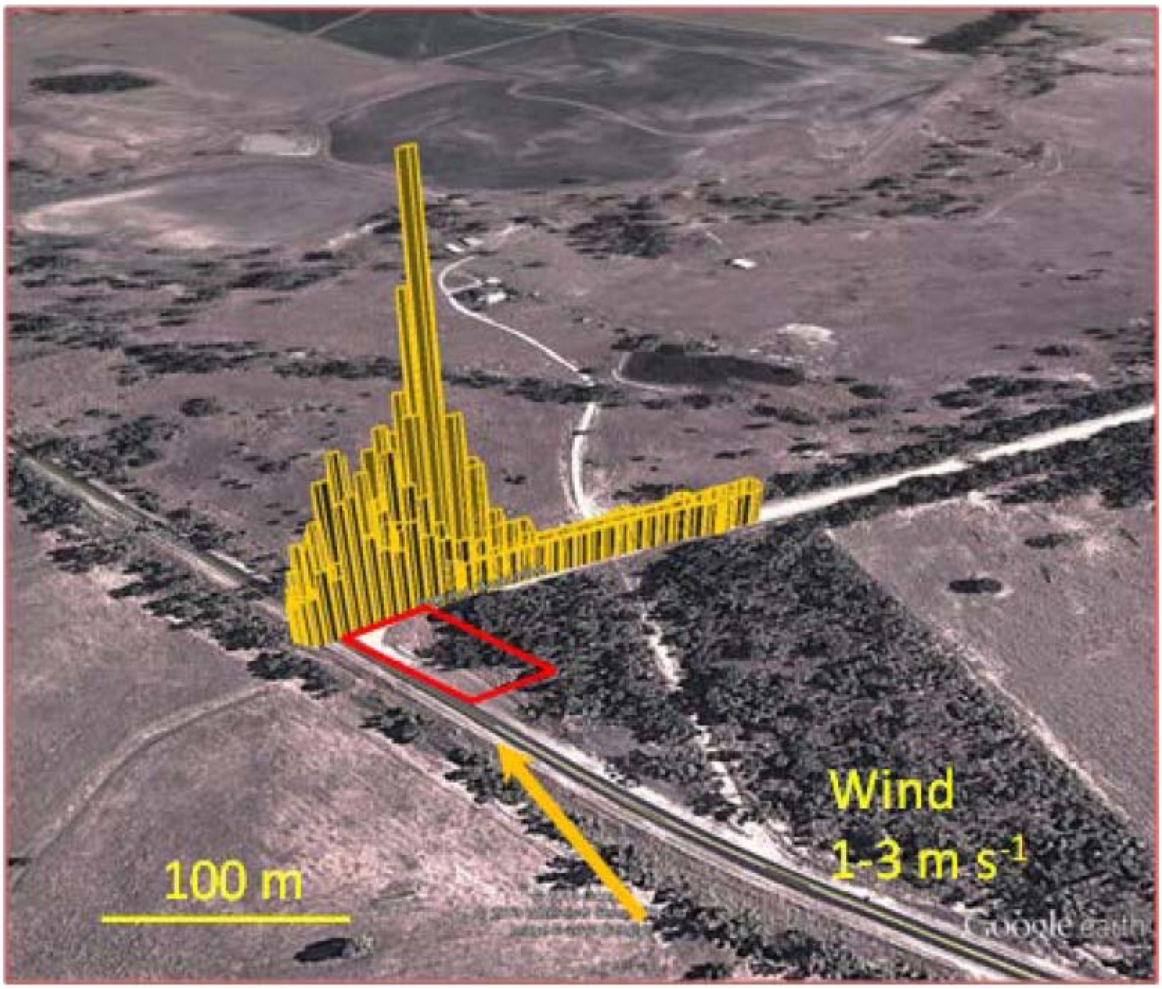

Figure 15 Methane concentration profile within a plume derived from a methane seep in Queensland (Source: Day et al., 2013).

3.5 Baseline surveys

An amendment to the Queensland *Water Act* requires proponents to undertake baseline assessments of water bores prior to the commencement of petroleum activities. These data are collated by the Office of Groundwater Impact Assessment within the Queensland government. This section reports on these data as it relates to methane. Figure 16 shows a map of the Surat Cumulative Impact Area with the dissolved methane measurements in groundwater from the baseline surveys. Harris et al. (2012) report on a subset of these surveys, but also include bore-head concentrations, which show a similar spatial distribution. They also show that methane exists in most formations at high concentrations. The collated baseline data shows a similar picture for the formations but the absence of formation information supplied by some of the proponents means that there is not much more information than in Harris et al. (2012). Harris et al. (2012) also reported on gas shows as found in drilling records within the Queensland government.

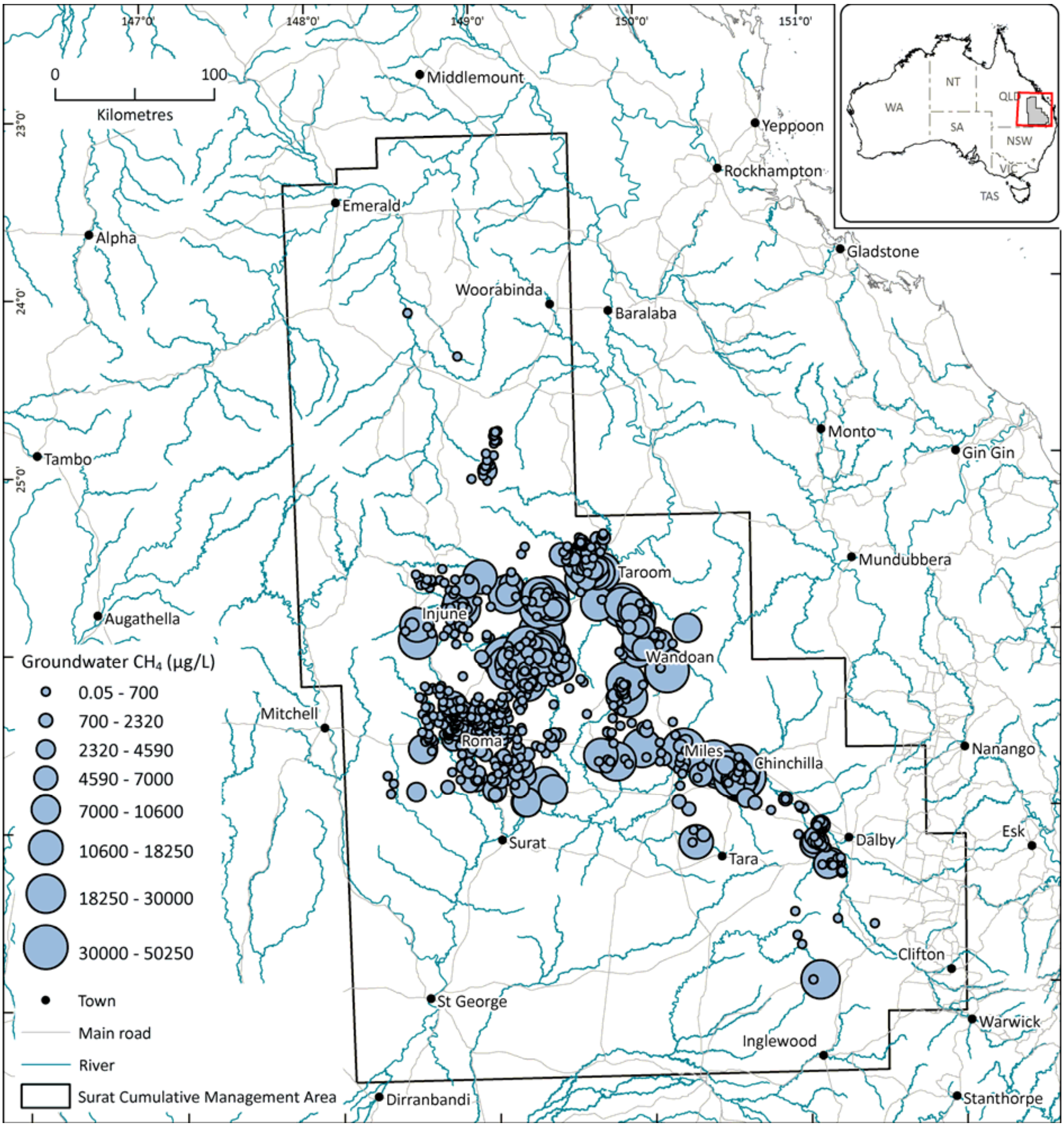

Figure 16 Map of the Surat Cumulative Impact Area with the dissolved methane measurements in groundwater from the baseline surveys (Data source: Queensland Water Commission, 2012).

Feitz et al. (2014) released a regional baseline set of hydrochemistry for the Denison trough and Surat Basin as a basis for developing future site-specific and semi-regional monitoring and verification programmes conducted by geological carbon capture and storage proponents. A map of methane concentrations as free gas is shown in Figure 17. This shows the presence of gas across the southern part of the region.

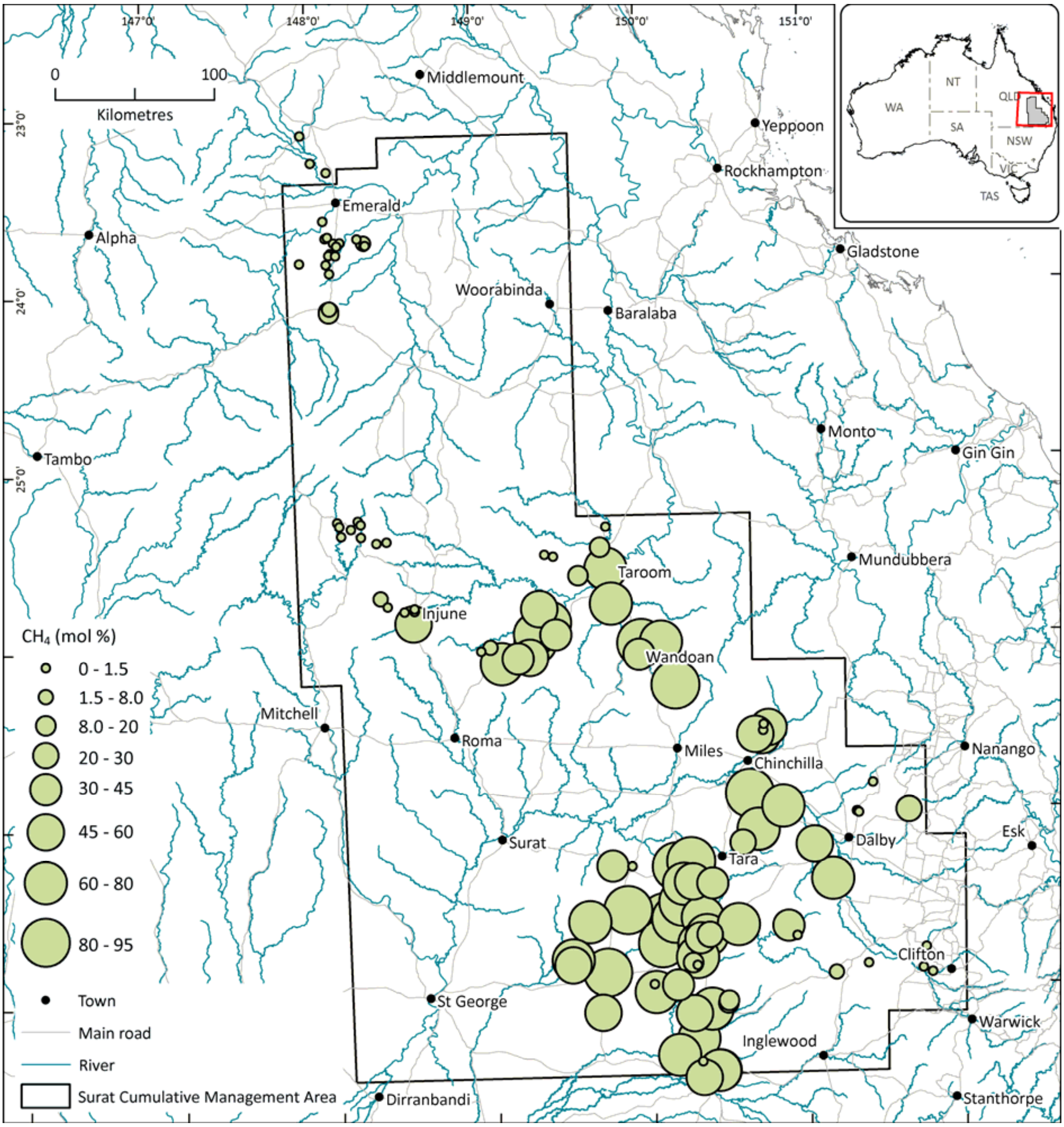

Figure 17 Map of the Surat Cumulative Impact Area with methane measurements in groundwater (methane concentrations as free gas) from a regional baseline set of hydrochemistry (Data source: Feitz et al., 2014).

3.6 Summary and Conclusions

This section has tried to look at various forms of information, as they exist without overlaying these with scientific interpretation. Generally, the information is consistent with the scientific picture that has been painted in other sections. More specifically:

1. Gas has been found historically when drilling for water and in water bores both in dissolved form and as free gas;
2. Gas is found in all geological formations;
3. The concentrations of gas vary in time according to atmospheric and other factors; and
4. Gas is broadly found across the region but is found at higher concentrations above features such as faults and above known gas reservoirs.

4 Relevant studies in Surat and Bowen basins, and elsewhere in Australia

The purpose of this section is to provide a brief description of activities being done or have been done recently that are relevant to this topic in Australia, especially in the Surat and Bowen Basins. The studies collated here do not include Queensland Government studies. Queensland Government has undertaken studies into any concerns over methane in water supplies and many of these have been referred to in previous section. The projects in this section are divided into 3 groups:

1. Methane in water bores;
2. Measurements of atmospheric methane; and
3. Hydrochemistry studies of groundwater.

4.1 Methane in water bores

There are three projects directly relevant to the topic of methane in water bores. These are:

- the Condamine seep study by Norwest/APLNG;
- the CRDC (Cotton Research and Development Corporation) methane baseline study in the Condamine by UNSW;
- the Southern Cross University baseline surveys in northern NSW.

4.1.1 CONDAMINE SEEP STUDY (NORWEST/APLNG)

In early 2012, seeps were reported in four Condamine River locations following a period of heavy flooding in the region. A subsequent Queensland Government investigation into the seeps found no evidence of safety risk or environmental harm. Anecdotal evidence suggests that at least one of the seeps may have been occurring for decades.

Norwest Corporation undertook a preliminary forensic study on behalf of Origin Energy into the causes of these seeps (Baldwin and Thoms, 2014). The region is at the early stages of development and no baseline survey had been previously done. Norwest found that gas originates from deeper aquifers such as the Springbok Sandstone and Walloon Coal Measures. They identified several possible mechanisms which could contribute alone or in combination to the seeps:

- Depressurisation – either from natural causes such as drought, or human activity such as water bores tapping the coal seams, CSG wells, or numerous open coal exploration bores;
- Repressurisation - impact of floods and aquifer recharge;
- Fractures, faults and springs - natural pathways for water and gas; and
- Capping and trapping - geological structures which “cap and trap” natural gas movement.

The Condamine River Gas Seep Investigation: Technical Report (Baldwin and Thoms, 2014) was subject to an independent scientific review coordinated by the Queensland Government’s Chief Scientist Dr Geoff Garrett.

Australia Pacific LNG is currently carrying out seismic survey analysis and constructing eight monitoring bores at four locations near the seeps. These monitoring bores feature real time telemetry data systems and will provide ongoing data on ground water levels and pressures.

4.1.2 CRDC METHANE BASELINE STUDY IN THE CONDAMINE (UNSW)

A project is being led by Associate Professor Bryce Kelly from the University of New South Wales to assess the extent of hydraulic connectivity between the Walloon Coal Measures and aquifers used by farmers in the Condamine Catchment in South-East Queensland. Apart from Associate Professor Bryce Kelly, project members include Professor Euan Nisbet and Dr Dave Lowry, Dr Dioni Cendón based at Australian Nuclear Science and Technology Organisation (ANSTO), and hydrogeologist Mark Hocking. A large focus of this study will be on methane. A baseline survey of both groundwater and the atmosphere (see next section) will be conducted. Professor Euan Nisbet and Dr Dave Lowry, from Royal Holloway, University of London, in association with colleagues from Royal Holloway, will conduct an air quality survey to map the concentration of methane in and around the irrigation districts and CSG production areas. In addition, UNSW researchers will measure the concentration of methane in the groundwater used for irrigation. They will 'fingerprint' the potential origin of the methane, by measuring the isotopes of carbon. As methane can be an indicator of connectivity between aquifers, this is part of a broader study of the connectivity involving examining the chemistry of the groundwater and mapping the geology of the region in 3D, analysing the historical groundwater level and chemical data sets, and examining pumping impact scenarios. Groundwater from 30 irrigation and observation bores in proximity to new CSG production and exploration wells in the Condamine Catchment have been sampled. Dr Dioni Cendón will lead a team from ANSTO who have for example analysed the major and minor ion chemistry and the isotopes of carbon, hydrogen and strontium in the groundwater.

4.1.3 SOUTHERN CROSS UNIVERSITY BASELINE SURVEYS IN NORTHERN NEW SOUTH WALES

Associate Professor Isaac Santos and his group in the Centre for Coastal Biogeochemistry research have been conducting hydrochemical studies in surface water bodies and groundwater in the Clarence-Moreton Basin in northern New South Wales to better understand how they may be impacted by coal seam gas development in the region (Tait et al., 2013). Much of the work at this stage is to develop a baseline database on the chemical composition of groundwater and streams potentially impacted by CSG exploration. The concentration of methane and associated isotopes are considered a priority. They are also providing a service for landholders to test water samples for methane.

4.2 Measuring Atmospheric Methane

The migration of methane from underground sources often does not end up in the water bores, but escapes to the atmosphere itself. With international concerns of climate change and requirements for greenhouse gas accounting, emissions that occur as a result of coal seam gas and other developments may be a significant contributor to greenhouse gases. These studies usually have this endpoint in mind, but provide information of the variability of methane emissions in space and time and hence on potential conduits of methane from underground.

4.2.1 FIELD MEASUREMENTS OF FUGITIVE EMISSIONS FROM EQUIPMENT AND WELL CASINGS (CSIRO)

Methane emissions were measured at 43 CSG wells – six in NSW and 37 in Queensland (Day et al., 2014). Measurements were made by downwind traverses of well pads using a vehicle fitted with a methane analyser to determine total emissions from each pad. In addition, a series of measurements were made on each pad to locate sources and quantify emission rates. Of the 43 wells examined, only three showed no emissions. The remainder had some level of emission but generally the emission rates were very low, especially when compared to the volume of gas produced from the wells. The principal methane emission sources were found to be venting and operation of gas-powered pneumatic devices, equipment leaks and exhaust from gas-fuelled engines used to power water pumps. Although the well pad emissions were low, a separate, larger source of methane was found on a gas relief vent on a water gathering installation close to one of the wells examined during this study.

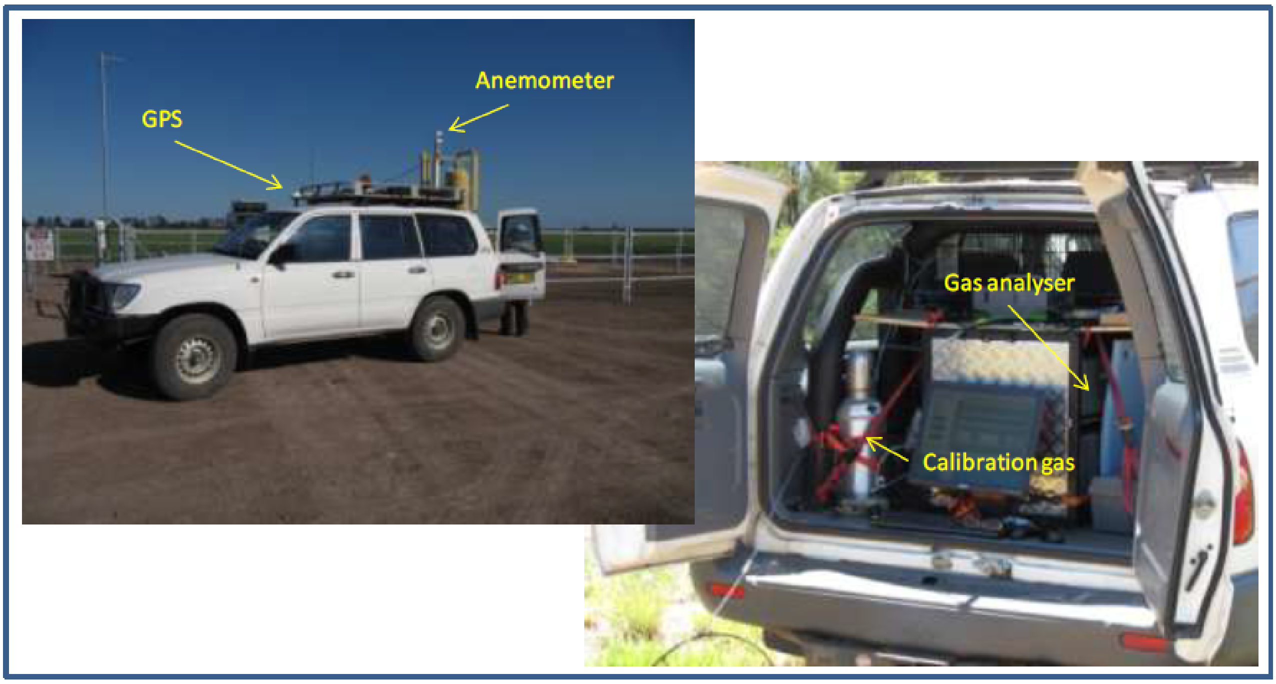

Figure 18 Photographs of the field vehicle with the GPS antenna and sonic anemometer are visible on the top of the vehicle (left hand photograph). The methane analyser and a calibration gas cylinder are shown in the rear of the vehicle (right hand photograph). (Source: Day et al., 2014).

4.2.2 ATMOSPHERIC METHANE CONCENTRATION MEASUREMENTS (SOUTHERN CROSS UNIVERSITY)

Atmospheric radon (^{222}Rn) and carbon dioxide (CO_2) concentrations were used (Tait et al., 2014) to gain insight into fugitive emissions in an Australian coal seam gas (CSG) field (Surat Basin, Tara region, Queensland). Atmospheric radon and CO_2concentrations were observed for 24 h within and outside the gas field. Both ^{222}Rn and CO_2 concentrations followed a diurnal cycle with night time concentrations higher than day time concentrations. Average CO_2 concentrations over the 24h period ranged from ~390 ppm at the control site to ~467 ppm near the centre of the gas field. A ~3 fold increase in maximum ^{222}Rn concentration was observed inside the gas field compared to outside of it. There was a significant relationship between maximum and average ^{222}Rn concentrations and the number of gas wells within a 3 km radius of the sampling sites (n = 5 stations; $p < 0.05$). A positive trend was observed between CO_2

concentrations and the number of CSG wells, but the relationship was not statistically significant. They hypothesized that the radon relationship was a response to enhanced emissions within the gas field related to both point (well heads, pipelines, etc) and diffuse soil sources.

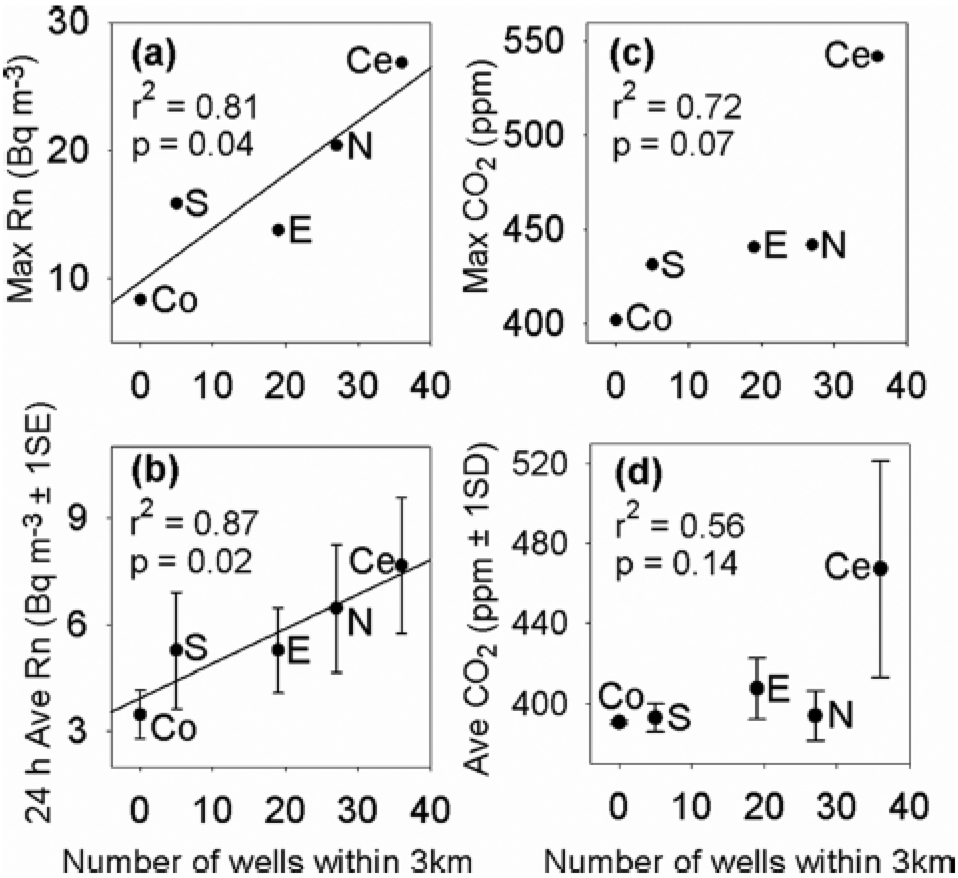

Figure 19 Results of atmospheric study conducted by Southern Cross University (Source: Tait et al., 2013)

4.2.3 CHARACTERISATION OF REGIONAL FLUXES OF METHANE IN THE SURAT BASIN, QUEENSLAND (GISERA PROJECT)

This GISERA project aims to address significant uncertainties associated with background seepage of methane and its detection and measurement in the Surat Basin, Queensland. Seepage is the diffusive flux of methane to the atmosphere through the land surface and water bodies, the localised flux of methane via connectivity pathways consisting of leads, faults and outcrops and the flux from agricultural bores. It does not consider the fugitive emissions of methane occurring as part of open cut and underground coal mines or emissions occurring from infrastructure (wells, compressors, associated water reticulation, or gas pipelines) associated with CSG production.

The research will provide:

(1) A desktop review and analysis of remote sensing imaging and direct detection (ground based flux) methods to quantify methane sources and fluxes. This activity is complete (Day et al., 2013);

(2) A field trial of methods at (i) a remote sensing pilot site, and (ii) a ground based direct detection and monitoring pilot site. The remote sensing pilot will test the acceptable method(s) developed in Task 1 for deployment within a defined test area and ability to detect methane seeps more broadly in the Upper

Condamine River catchment. The ground detection and monitoring pilot will test in situ measurement of on-ground methane fluxes at up to two pilot sites. Isotopic chemical tracers will assist in distinguishing coal methane seeps from biogenic methane sources. Each pilot is contingent on results from Task 1 and the client's input at decision points in the project; and,

(3) broad scale application of methods to a larger region in the Upper Condamine River catchment. This research will provide baseline monitoring data of methane seepage fluxes over different seasons. The final design is contingent on results from Tasks 1 and 2, their successful application and the client's input at decision points.

4.3 Studies of groundwater hydrochemistry

The hydrochemistry of groundwater can inform us about the sources of methane and other organics, processes in its formation, advective transport of constituents and reaction along the pathway and mixing processes. It is useful for understanding connectivity of aquifers and potential for leakage between them under stresses caused by water and gas development, connectivity with valued ecosystems and streams; and understanding potential for carbon capture and storage. The following are three recent or current studies. There are other more recent initiatives, such as that from the Centre for Coal Seam Gas at The University of Queensland, who are developing a publicly available web-based atlas of water chemistry data for CSG Fields. Other relevant research is that by Golding et al. (2013), Hamilton et al. (2012 and 2014), and Papendick et al. (2011) on fingerprinting the actual coal- bearing formations by using stable isotopes.

4.3.1 GEOSCIENCE AUSTRALIA AND GEOLOGICAL SURVEY OF QUEENSLAND SURAT AND BOWEN BASINS GROUNDWATER SURVEYS HYDROCHEMISTRY DATASET (2009-2011)

Geoscience Australia, the Geological Survey of Queensland and the Queensland Department of Mines and Energy (Feitz et al., 2014) are aiming to characterise the regional hydrochemistry of the Denison Trough and Surat Basin for the purposes of assessing their suitability for greenhouse gas storage and recovery. They have trialled different groundwater monitoring strategies to produce a regional baseline reference set for future site-specific and sub-regional monitoring and verification programmes conducted by geological storage proponents. The dataset provides a reference of hydrochemistry for future competing resource users, including coal seam gas proponents. Many of the analyses are needed for forensic studies for coal seam gas.

4.3.2 HYDROCHEMISTRY OF COAL SEAM GAS GROUNDWATERS IN THE SURAT AND CLARENCE-MORETON BASIN AND THEIR APPLICATION AS INDICATORS OF PROCESSES (QUEENSLAND UNIVERSITY OF TECHNOLOGY/CSIRO)

A group led by Professor Malcolm Cox in the School of Earth, Environmental and Biological Sciences, Queensland University of Technology has been studying the hydrochemistry of both the Surat and Clarence-Moreton basins in order to better understand how groundwater chemistry may influence the development of methane and vice-versa.

Two PhD projects assessing the hydrochemical and isotopic variability of groundwater in the Condamine River catchment (PhD students Des Owen and Jorge Martinez) are likely to improve the understanding of the process of methane formation, but will also provide useful information on the groundwater chemistry associated with methane formation. This enables better identification of methane sources within shallow groundwater and connectivity between aquifers, particularly between the Walloon Coal Measures and the Condamine River alluvium.

In an on-going PhD project in the Logan-Albert catchment within the Clarence-Moreton Basin, PhD student Clément Duvert has compared hydrochemistry, rare earth elements and isotopes of groundwater samples from the Walloon Coal Measures and overlying alluvial aquifers collected during dry and wet periods. The study demonstrates that there can be substantial temporal variability of hydrochemistry and isotopes within the Walloon Coal Measures and the alluvial aquifers at some bore sites, highlighting the importance of collecting time-series data where possible.

As part of a postdoctoral research project funded by the NCGRT, Dr. Matthias Raiber (now CSIRO) has in collaboration with Dr. Andrew Feitz (Geoscience Australia) analysed methane concentrations and the isotopic composition of δ^2H and $\delta^{13}C$ of methane on approximately 50 groundwater samples from the Walloon Coal Measures and other formations throughout the Clarence-Moreton and eastern Surat basins. The study indicates that methane concentrations within the Walloon Coal Measures are spatially highly variable, likely due to complicated hydrological processes (e.g. groundwater recharge). In addition, the study confirmed that methane is also present in other formations.

4.3.3 MONITORING OF HYDROCHEMICAL AND ISOTOPIC CHARACTERISTICS OF CSG FORMATION WATERS, ADJACENT AQUIFERS AND SPRINGS (GISERA).

This ongoing project is aimed[6] at: (i) a comprehensive hydrochemical and isotopic characterisation of groundwater and formation water within the proposed CSG extraction area prior to development; (ii) developing protocols for monitoring aquifers and formation water over the time period of extraction and post-development and (iii) establishing a set of criteria for ongoing assessment of the monitoring program and implications for aquifer interactions. A practical aim of the project is to provide a means of monitoring the progress and impact of large scale pumping and to inform potential modification of the pumping process to minimise potential impacts on spring-fed or baseflow ecosystems. More specifically, work is proceeding on 1) source of water in springs; 2) hydrochemical and isotopic sampling of the Hutton Formation (Figure 20) and 3) testing a technique for obtaining helium concentrations in quartz as proxy for helium in pore waters of low permeable formations such as aquitards (Smith et al., 2013).

4.3.4 REVIEW OF DISSOLVED HYDROCARBONS IN GROUNDWATER IN THE SURAT AND BOWEN BASINS (GISERA)

This project aims[7] to:

1. Collate and provide a summary of the available information on existing hydrocarbons in groundwater in the Surat and Bowen basins as a context and potential explanations for possible future detection and reporting of hydrocarbons during compliance monitoring programmes;
2. Outline strategies related to differentiation of naturally occurring hydrocarbons and those inadvertently introduced during drilling, completion and hydraulic stimulation; and

[6] http://www.gisera.org.au/research/research_progress.html
[7] http://www.gisera.org.au/research/research_progress.html

3. Interpretations on possible sources of the hydrocarbons encountered based on previous studies and new information gained through additional sampling/monitoring data acquired by the companies involved.

All hydrocarbon compounds of concern (TPHs, BTEX and PAHs) will be considered as well as phenols, for which concerns also exist, subject to data availability.

Figure 20 Sampling during the GISERA hydrochemistry project (Photograph courtesy: CSIRO).

4.4 Summary and Conclusions

The nature of research funding and research institutions means that there is a certain amount of coordination, but it is far from perfect. A number of organisations such as the Office of Groundwater Impact Assessment in Queensland Government, Office of Water Science in the Australian Government, Geoscience Australia, Gas Industry Social and Environmental Research Alliance (GISERA), production companies and Research and Development Corporations such as Cotton all try to ensure the best outcomes of their investments through coordination and communication. Technical meetings and scientific conferences facilitate exchange of ideas and results. However, there are reasons why coordination is far from perfect. The innovation sector is driven by competition: competition for funding, competition of ideas and competition between specialist skills and equipment. Also, this is a contentious topic with different sectors having different agendas and interests. Both of these issues can lead to a seeming lack of coordination. There is clearly a balance to be reached. A lack of coordination can lead to duplication, wastage of time of scientific specialists and specialist facilities and not achieving larger outcomes. Too much coordination leads to a lack of tension that drives thinking and discussion and too much focus on this topic or that. Each person will have a different view as to where this balance sits. However, it is possible to make some general comments on the relativity of the three topic areas.

There does appear to be good coordination in the hydrochemistry area. In discussions, most were aware of others working in the area and the type of studies being conducted. There appear to be different institutions coordinating work in this area; there are several papers in this area and there is a long history of collaboration in the groundwater area. On the other hand, the provision of baseline information and targeted studies of processing facilities is relatively new and there appears to be less coordination in this space. Atmospheric studies are often driven by greenhouse gas accounting, which is different in nature to assessing risks of methane in shallow groundwater. Nonetheless, it can provide useful information on the topic. The studies of methane in shallow groundwater appear to be a lower priority for both state and Australian governments, perhaps left for the other sectors. However, as has been shown in this report, the nature of the measurements and processes strongly means that coordination needs to occur; otherwise we may be in a situation of not being able to assess impacts or emerging issues. The work has been a higher priority in the USA and Canada, perhaps due the number of people living in shale gas and coal seam gas areas as well as the amount of infrastructure. However, the focus has led to a situation where there is a quick response to emerging trends and risks.

5 Conclusions

Methane in water bores is a major concern in areas of coal seam gas development. There are risks such as gas lock in pumps, colour and odour impacts from water quality changes, toxicity due to other gases and build up of gases affecting the integrity of the bores. A review was conducted of the state of the art of methods for investigating gas in water bores and analysis of resulting data. The historical presence of gas in water bores in the Surat and Bowen basins since the early 1900s was also reviewed. Information from this review is to be used to investigate and respond to reports of increased gas content in individual water bores across a large area in Queensland. For such work to be effective, it is critical to have a good understanding of (i) the different sources of methane gas in the subsurface, (ii) the processes responsible for gas migration and mixing and thus for variability in gas concentration, and (iii) methods for measuring gas in water bores.

Methane in water bores may be present as dissolved gas in solution and/or as free gas. Dissolved methane gas usually only exsolves from a still solution if the concentration of methane in the fluid exceeds its solubility. Gas solubility varies with temperature, salinity, and pressure: it decreases with increasing temperature and salinity and increases with increasing pressure. Coal seam gas-derived methane will often co-exist with other gases such as short chain hydrocarbon gases such as ethane, propane and butane, as well as carbon dioxide, nitrogen and hydrogen sulfide. The relative abundance of such hydrocarbon gases (and their isotopic signatures) may be used to determine the gas source.

When sampling for methane in groundwater, the sample should preferably be collected from deep within the bore close to the screen either by low flow pumping or an in situ device such as a diffusion sampler. Appropriate sampling techniques reviewed include the inverted bottle method as used for both free and dissolved gas and gas extraction samplers.

Methane concentrations have been shown to be highly variable in space and time. This variability can be related to processes that cause methane concentrations to increase and decrease. Some studies have shown that sampling error and analytical error also contribute to this variability.

When analysing methane data, careful consideration should be give to the following issues:

- methane occurs naturally in groundwater and in the vapour phase of the unsaturated zone, especially in areas where there is coal seam gas;
- methane concentrations will have been exacerbated by depressurisation caused by pumping for water and conventional gas development over time, as well as exploration for oil and gas before any coal seam gas development occurred;
- changes in methane may be due to a range of causes other than coal seam gas development. In many cases overseas, investigation of complaints have found that poor maintenance of water bores resulted in microbially-mediated methane production as a cause of changes in water quality;
- variability with time of measured methane concentrations due to sampling and analytical error and processes leading to presence of methane in the water bore; and
- variability of concentration of methane and related constituents within each of the different sources of methane.

For a better understanding of the impact of coal seam gas extraction and depressurisation on methane in the groundwater resource as a whole, a more systematic sub-regional and regional strategy is required.

This will allow the identification of gradual or sudden changes, irrespective of cause, and understanding of periodic changes of methane that may not be related to coal seam gas extraction. Such a strategy will need a sampling and analysis methodology that is robust enough to provide consistent measurements with sufficient sensitivity to detect trends in time and spatial patterns. However, the effort that goes into any monitoring program needs to be commensurate with the risks and customized to highlight mitigation measures. For some of the risks, there is a well-established mitigation process established and some of this may not require an expensive monitoring program. However, for evaluation of the larger effects of the impacts of a coal seam gas development or for better delineating causes of poorer bore quality, more comprehensive and consistent monitoring is required.

To measure changes in state of individual water bores and the groundwater resource as a whole requires first of all a baseline survey across relevant bores. For any detection of change or trend, the change needs to be larger than the noise in the baseline. This noise could be due to variability related to sampling and analysis but it also can be related to real processes that cause methane concentrations increase and decrease. To provide confidence about the extent of change, it is important to quantify the variability of the analyses.

Overseas experience has shown that consistent and reliable measurement of methane concentrations with sufficiently low variability requires focus on training, adherence to strict protocols, including split and duplicate samples, and consistency in the information recorded. Best overseas practice often has data stored on an audited transparent database.

Most methane in water bores is of biogenic or thermogenic origin; the gas sources grade from biogenic to thermogenic with depth. Biogenic methane production is the most common of the processes in shallow groundwater systems and involves bacterial decomposition of organic matter in the absence of oxygen through either fermentation of organic matter or reduction of carbon dioxide. Thermogenic methane is formed by the thermal breakdown of complex hydrocarbons resulting from decomposition of organic material largely originating in ancient shales. Thermogenic gases typically originated at great (1000s of meters) depths; however, over geologic time these gases may have migrated far from the original source area and subsequently accumulated at shallower depths.

Dissolved methane can exist in the groundwater near a water bore. When the water bore is pumped, water pressures in both the bore and the adjacent formation are decreased. Such a decrease in pressure can lead to methane degassing as water is drawn into the bore. These declines in pressure could lead to enhanced methane degassing and migration from increasingly larger areas around the bore.

Methane migration can also be affected by water, oil and gas developments, i.e. when water or gas production bores provide conduits through the different geological layers. Such borehole breaches present a number of opportunities for leakage of fluids in the vertical direction.

The ability to identify the sources of any high concentrations of methane in bores or changes requires measurements of other constituents using isotopes of hydrogen and carbon of methane and associated wet gas components. Other useful measurements are i) the stable carbon isotope ratio of dissolved inorganic carbon, which may be used to identify any bacterial consumption of methane that has occurred between the source and the bore and ii) the radioactive carbon isotope (^{14}C) which identifies a younger source of carbon originating from shallower groundwater unrelated to coal seams targeted for CSG extraction.

There has been a long history of methane detected in existing water bores or during drilling for water in the Surat and Bowen basins, dating back to the beginning of the twentieth century. The methane is found at higher concentrations above features such as faults and above known gas reservoirs.

There are a number of recent and current projects investigating issues related to methane in water bores in Queensland and NSW. For instance, the study of gas bubbling in the Condamine River showed that the source of the gas was from deeper aquifers. The study could not rule out any specific pathways or causes for any increase in gas bubbling.

Glossary

ANSTO: Australian Nuclear Science and Technology Organisation

Asphyxiation: A condition in which an extreme decrease of oxygen in the body accompanied by an increase in the concentration of carbon dioxide leads to loss of consciousness or death.

Artesian aquifer: A confined aquifer in which the pressure head of the groundwater rises above the upper confining layer of the aquifer. If the pressure is sufficient to cause the bore to flow at the surface, it is called a flowing artesian aquifer.

Bopd: barrels of oil per day

BTEX: Benzene, Toluene, Ethylbenzene, Xylene

Buoyancy: the tendency or capacity to remain afloat in a liquid or rise in air or gas

CSG: coal seam gas

CSGCU: Coal Seam Gas Compliance Unit

EC: electrical conductivity

GISERA: Gas Industry Social and Environmental Research Alliance

PAH: Polycyclic aromatic hydrocarbons

ppm: parts per million

TPH: Total petroleum hydrocarbon

VSMOW: Vienna Standard Mean Ocean Water

VPDB: Vienna Pee Dee Belemnite

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